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Ogawa et al.

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(45) **Date of Patent: Aug. 2, 2016**

(54) **FUEL CELL MODULE**

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(73) Assignee: **HONDA MOTOR CO., LTD.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(2) Date: **Apr. 24, 2015**

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H01M 8/04 (2016.01)
H01M 8/06 (2016.01)
H01M 8/12 (2016.01)
H01M 8/24 (2016.01)
C01B 3/38 (2006.01)

(52) **U.S. Cl.**
CPC ***H01M 8/04022*** (2013.01); ***C01B 3/384*** (2013.01); ***H01M 8/04268*** (2013.01);

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CPC C01B 3/384; C01B 2203/066; C01B 2203/0811; C01B 2203/1604; C01B 2203/0233; H01M 8/0612; H01M 8/04022; H01M 8/04268; H01M 8/0618; H01M 8/0662; H01M 8/1246; H01M 8/24; H01M 2008/1293; H01M 2250/20; Y02T 90/32; Y02E 60/50; Y02E 60/525; Y02E 60/324
See application file for complete search history.

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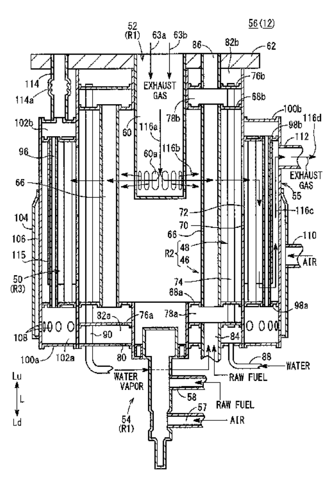
(57) **ABSTRACT**

A fuel cell module includes a first area where an exhaust gas combustor and a start-up combustor are provided, an annular second area around the first area and where a reformer and an evaporator are provided, and an annular third area around the second area and where a heat exchanger is provided. A circumscribed non-uniform flow suppression plate is provided along the minimum circumscribed circle which is tangent to outer surfaces of heat exchange pipes of the heat exchanger.

7 Claims, 20 Drawing Sheets



(52) **U.S. Cl.**
CPC ***H01M8/0612*** (2013.01); ***H01M 8/0618*** (2013.01); ***H01M 8/0662*** (2013.01); ***H01M 8/1246*** (2013.01); ***H01M 8/24*** (2013.01); *C01B 2203/0233* (2013.01); *C01B 2203/066* (2013.01); *C01B 2203/0811* (2013.01); *C01B 2203/1604* (2013.01); *H01M 2008/1293* (2013.01); *H01M 2250/20* (2013.01); *Y02E 60/324* (2013.01); *Y02E 60/50* (2013.01); *Y02E 60/525* (2013.01); *Y02T 90/32* (2013.01)

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This application is co-pending with U.S. Appl. No. 14/438,339, which was filed in the United States Patent and Trademark Office on Apr. 24, 2015, and U.S. Appl. No. 14/438,344, which was filed in the United States Patent and Trademark Office on Apr. 24, 2015.

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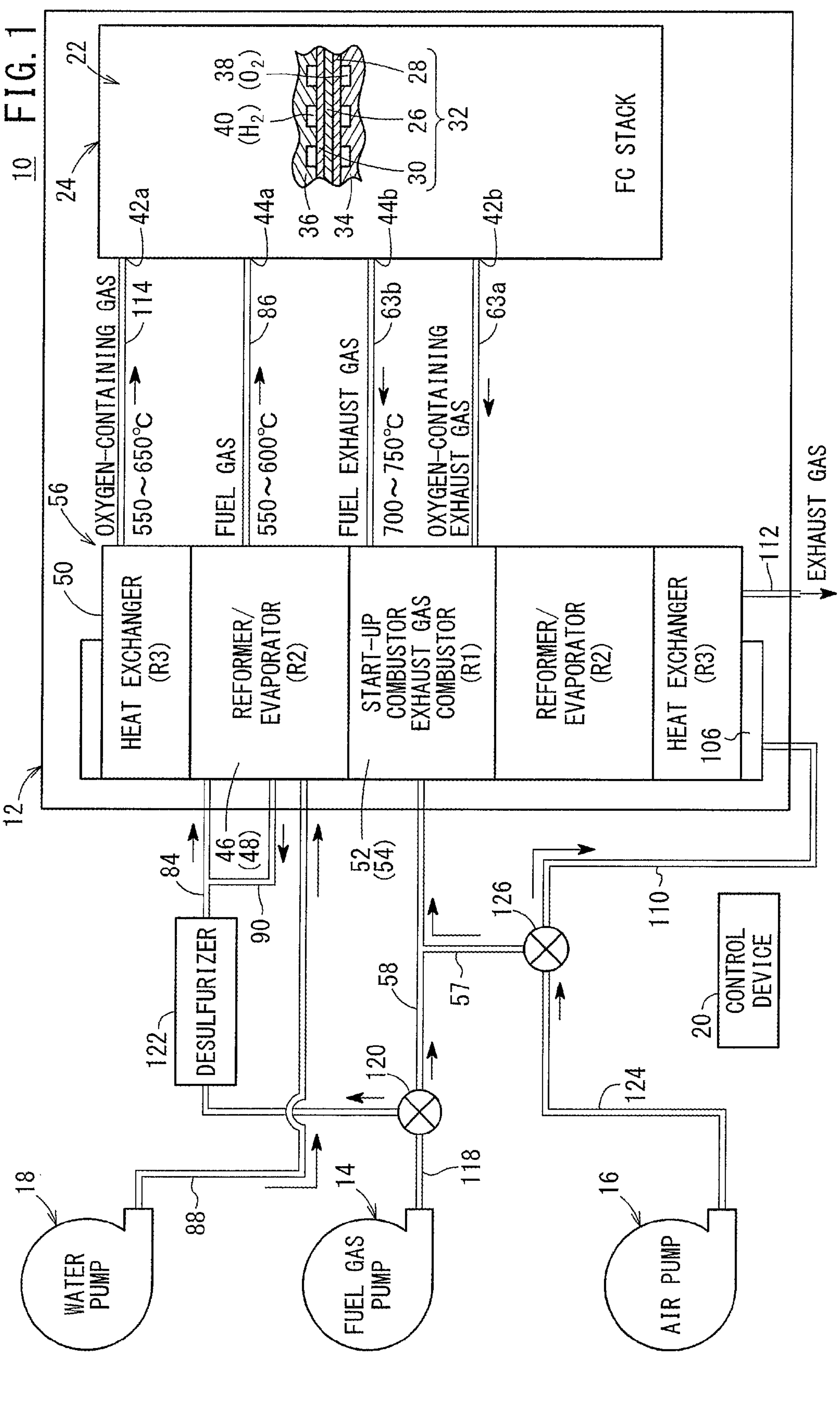
FIG. 1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114
FUEL GAS
550～600°C
86
FUEL EXHAUST GAS
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63b
OXYGEN-CONTAINING EXHAUST GAS
63a
56
50
HEAT EXCHANGER (R3)
REFORMER/ EVAPORATOR (R2)
START-UP COMBUSTOR EXHAUST GAS COMBUSTOR (R1)
REFORMER/ EVAPORATOR (R2)
HEAT EXCHANGER (R3)
106
112
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46 (48)
52 (54)
84
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122
58
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CONTROL DEVICE
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WATER PUMP
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FUEL GAS PUMP
14
AIR PUMP
16

FIG. 2

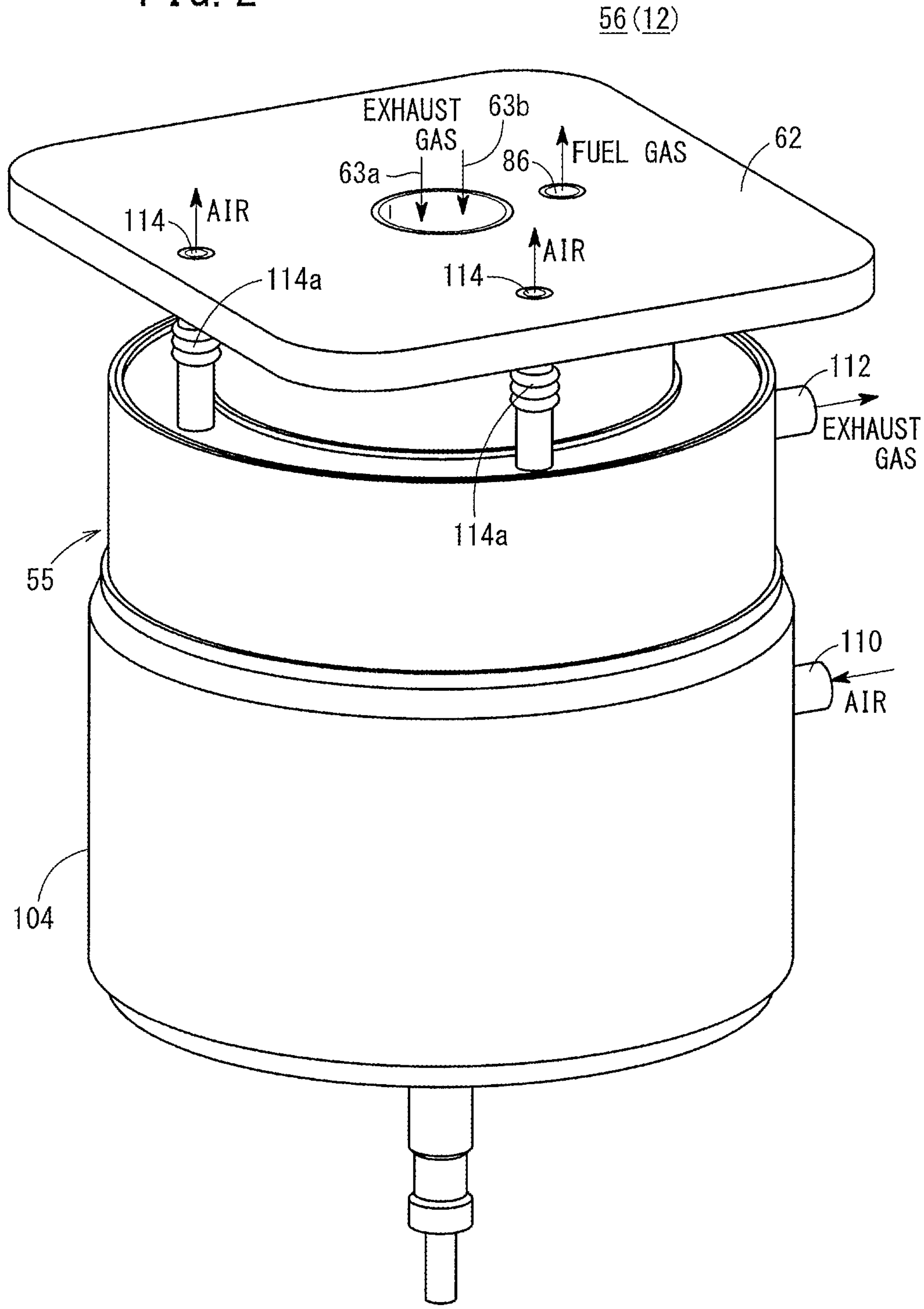
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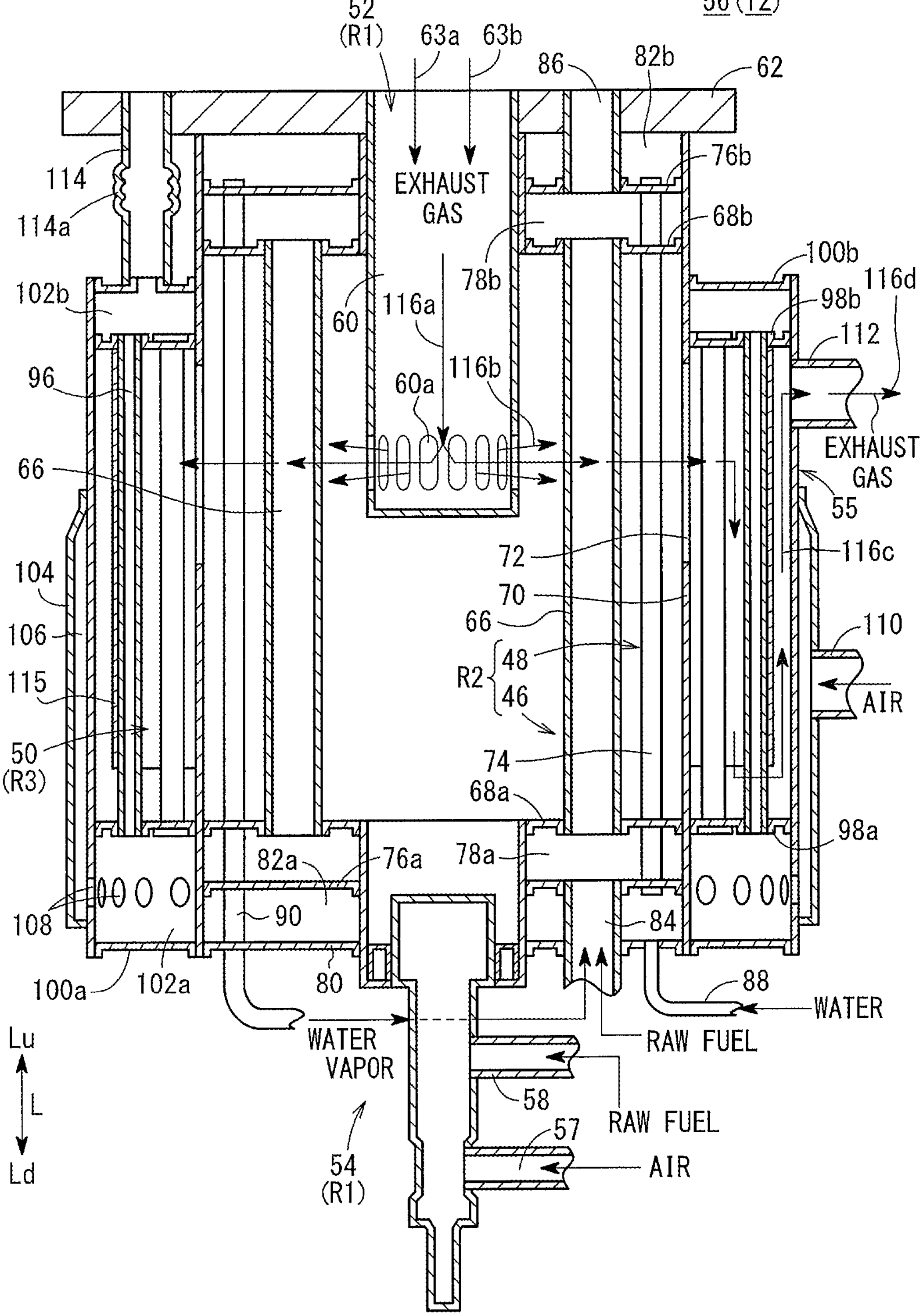
FIG. 3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60a
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116c
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115
48
R2
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(R3)
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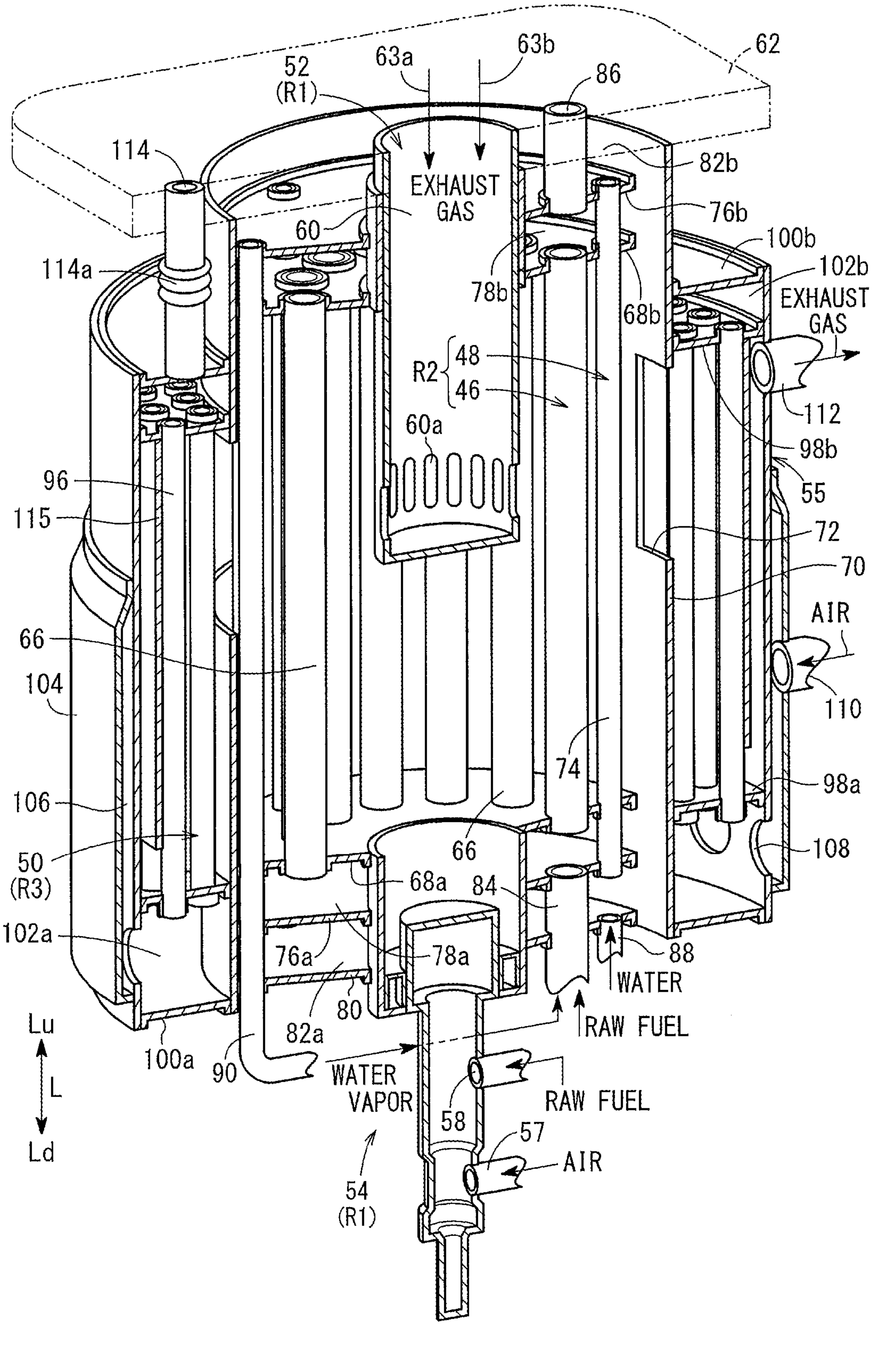
(R1)

FIG. 4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GAS
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(R3)
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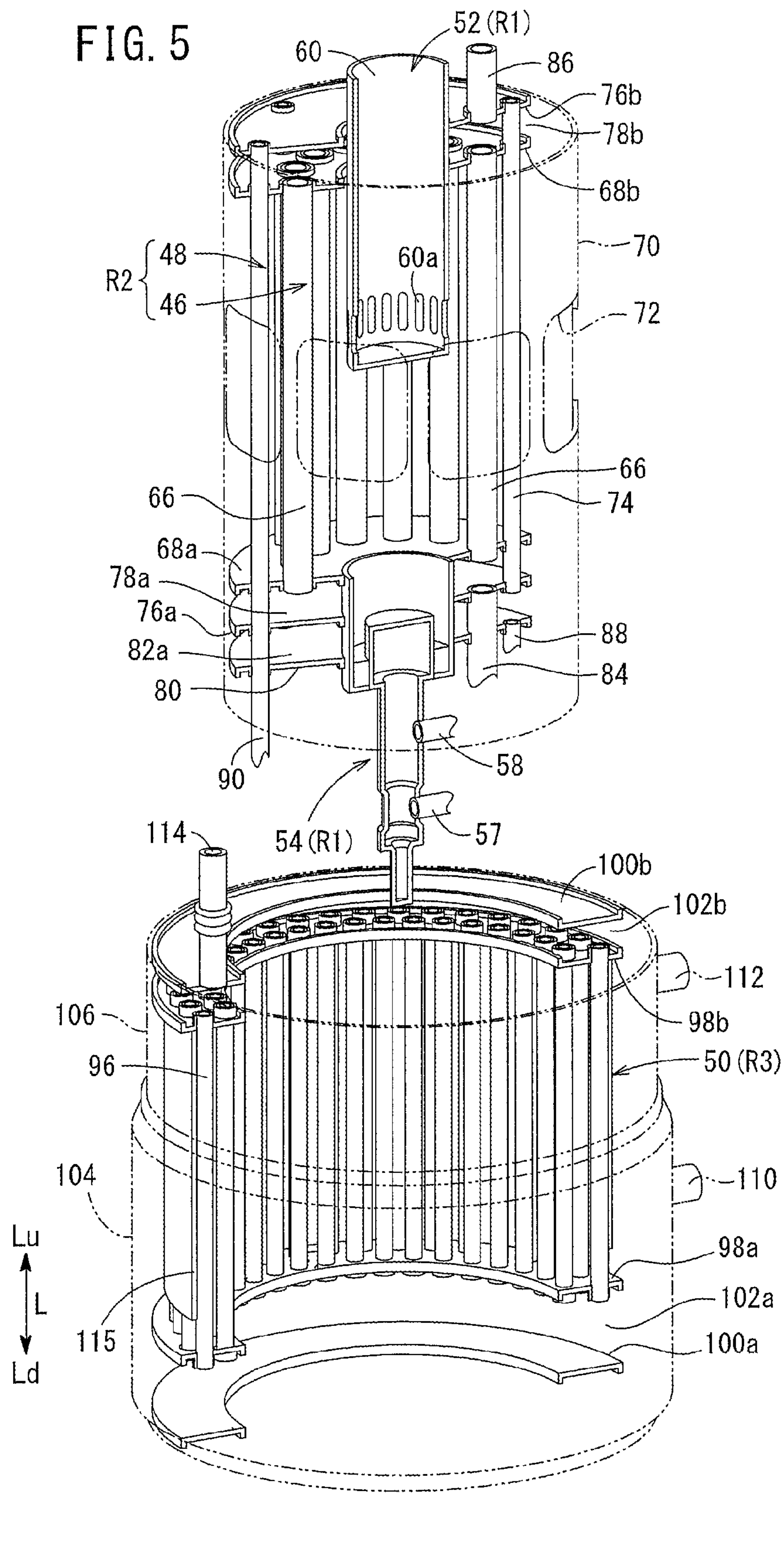
FIG. 5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54 (R1)
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FIG. 6

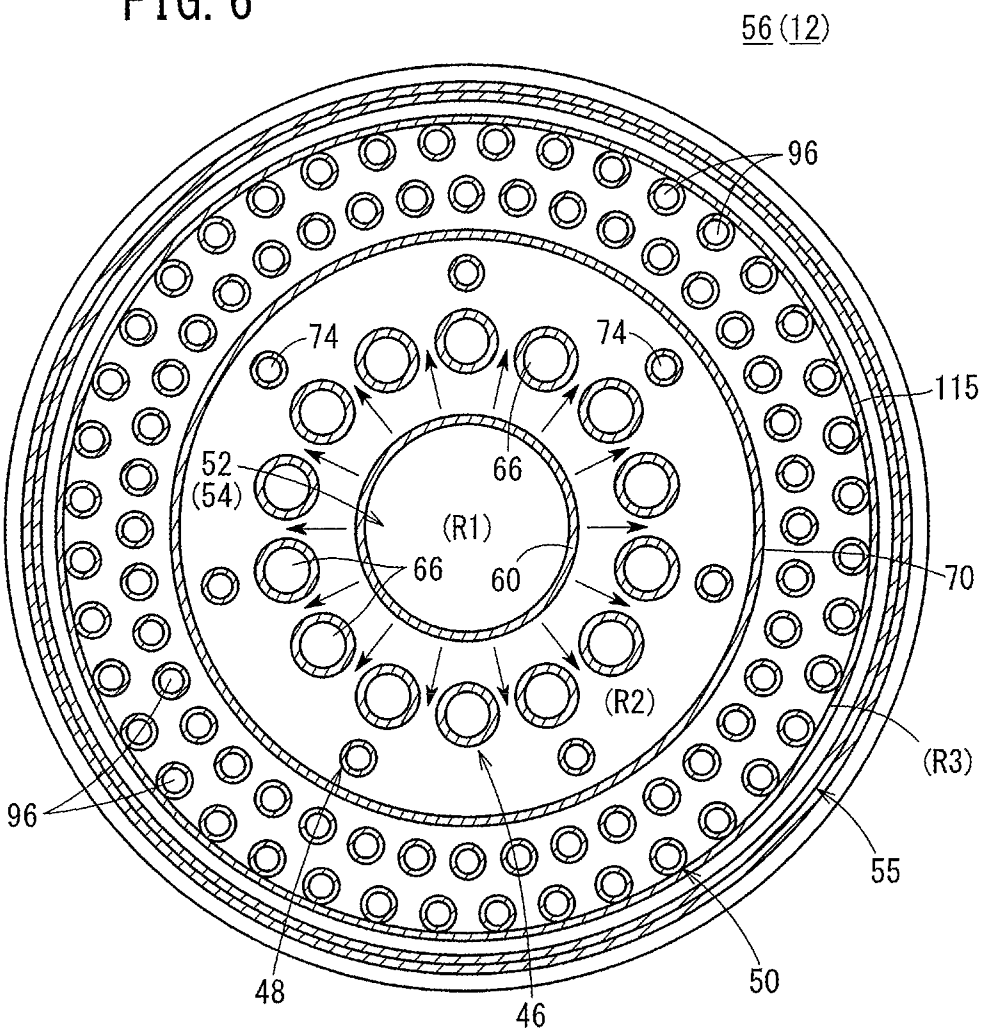
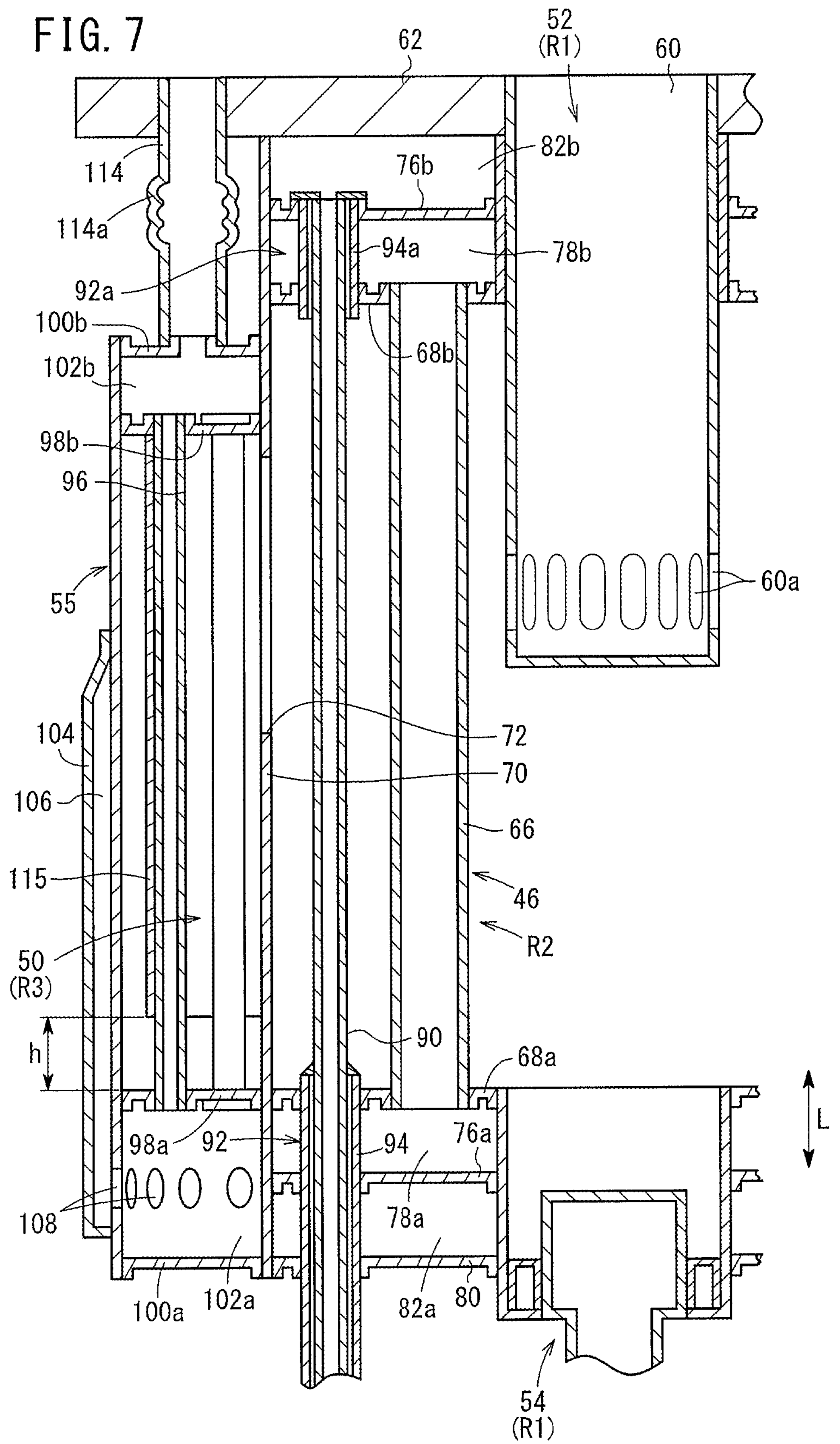


FIG. 7



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(R1)

FIG. 8

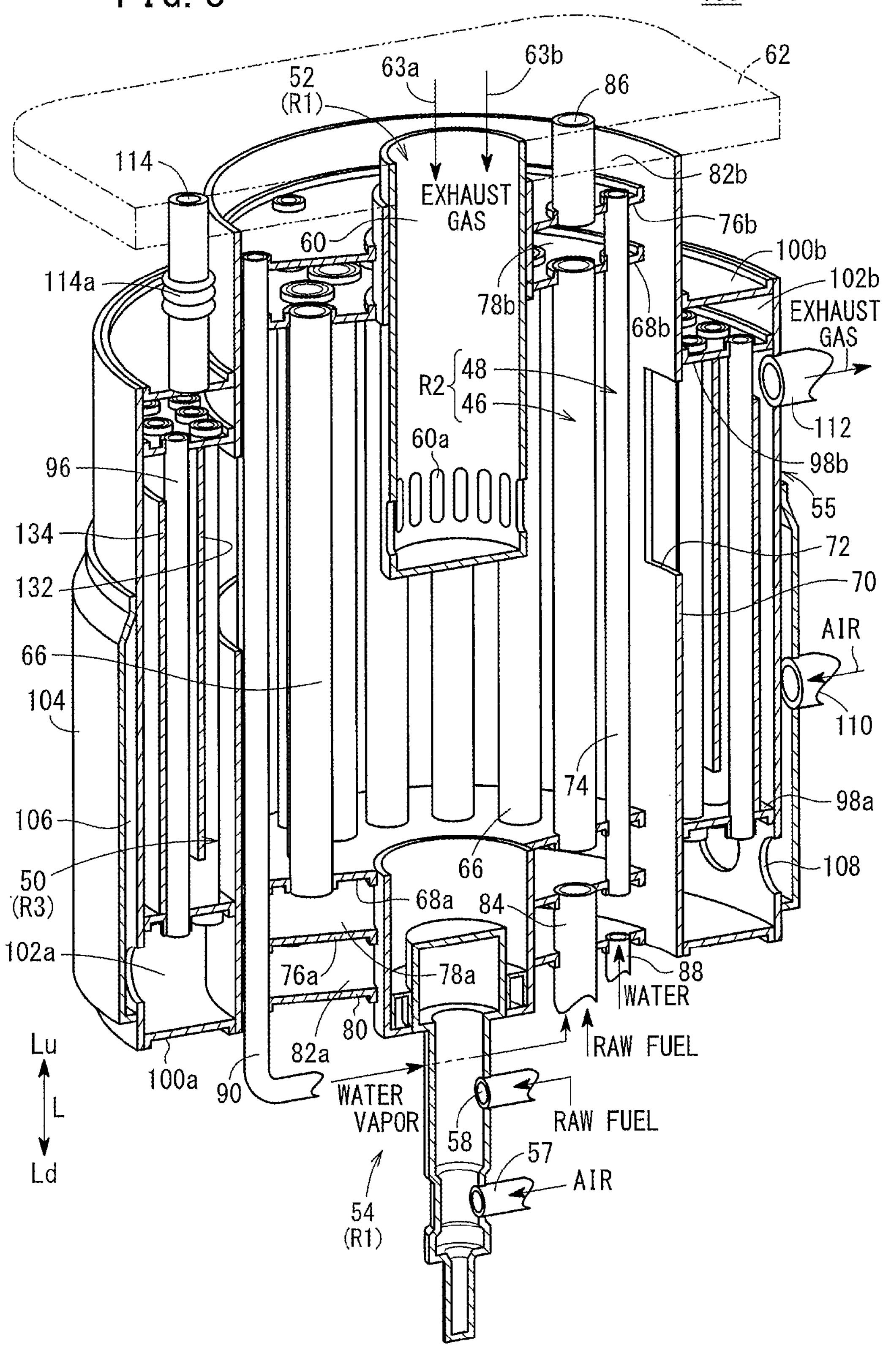
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FIG. 9

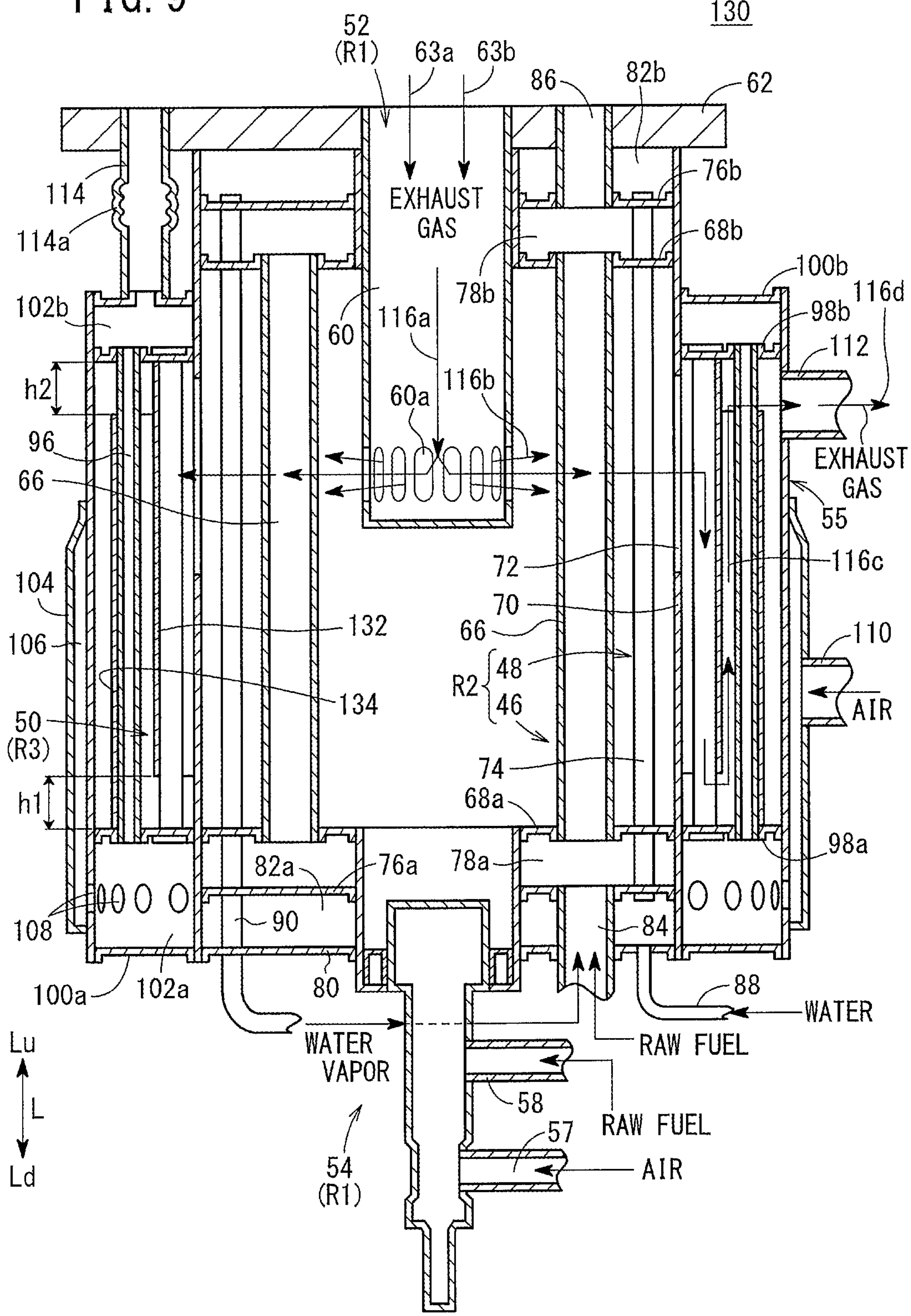
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FIG. 10

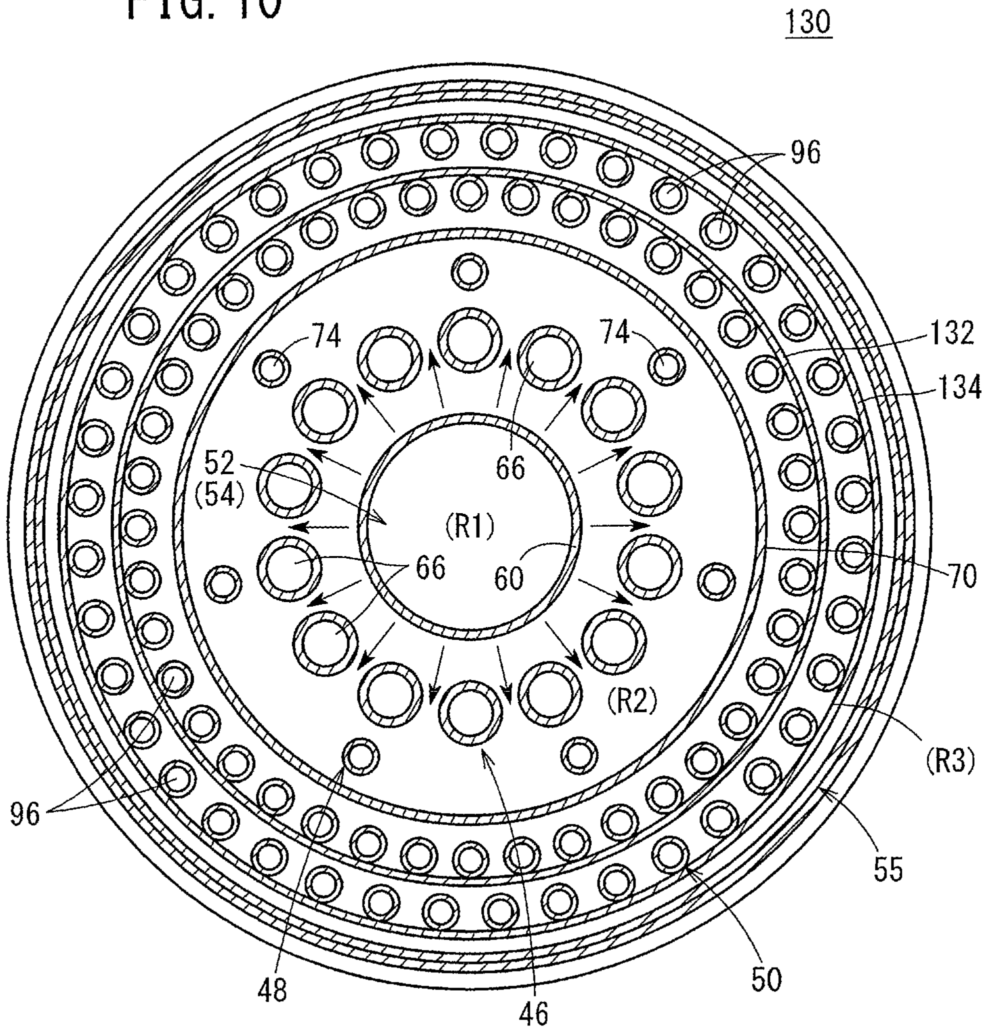

FIG. 11

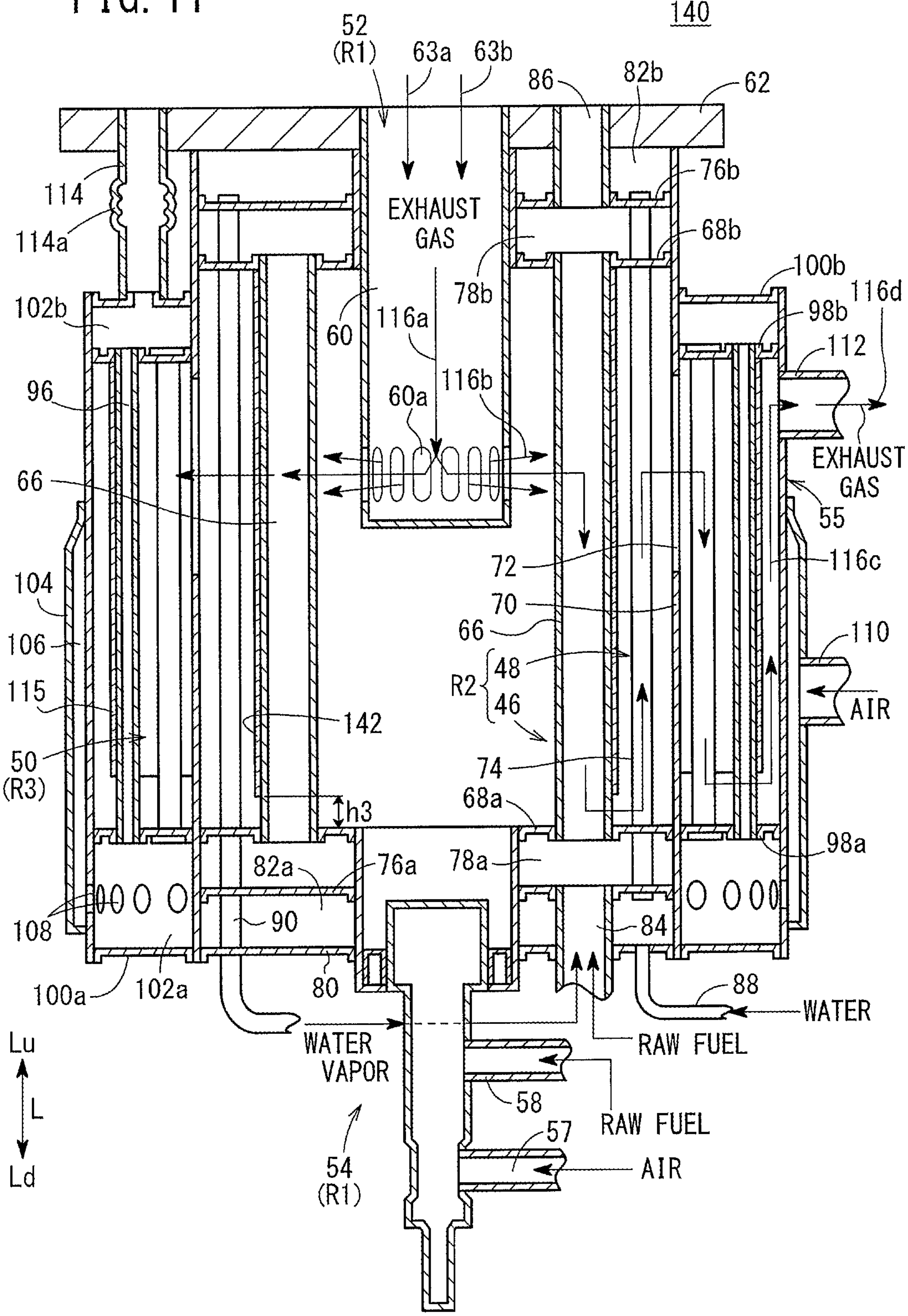
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FIG. 12

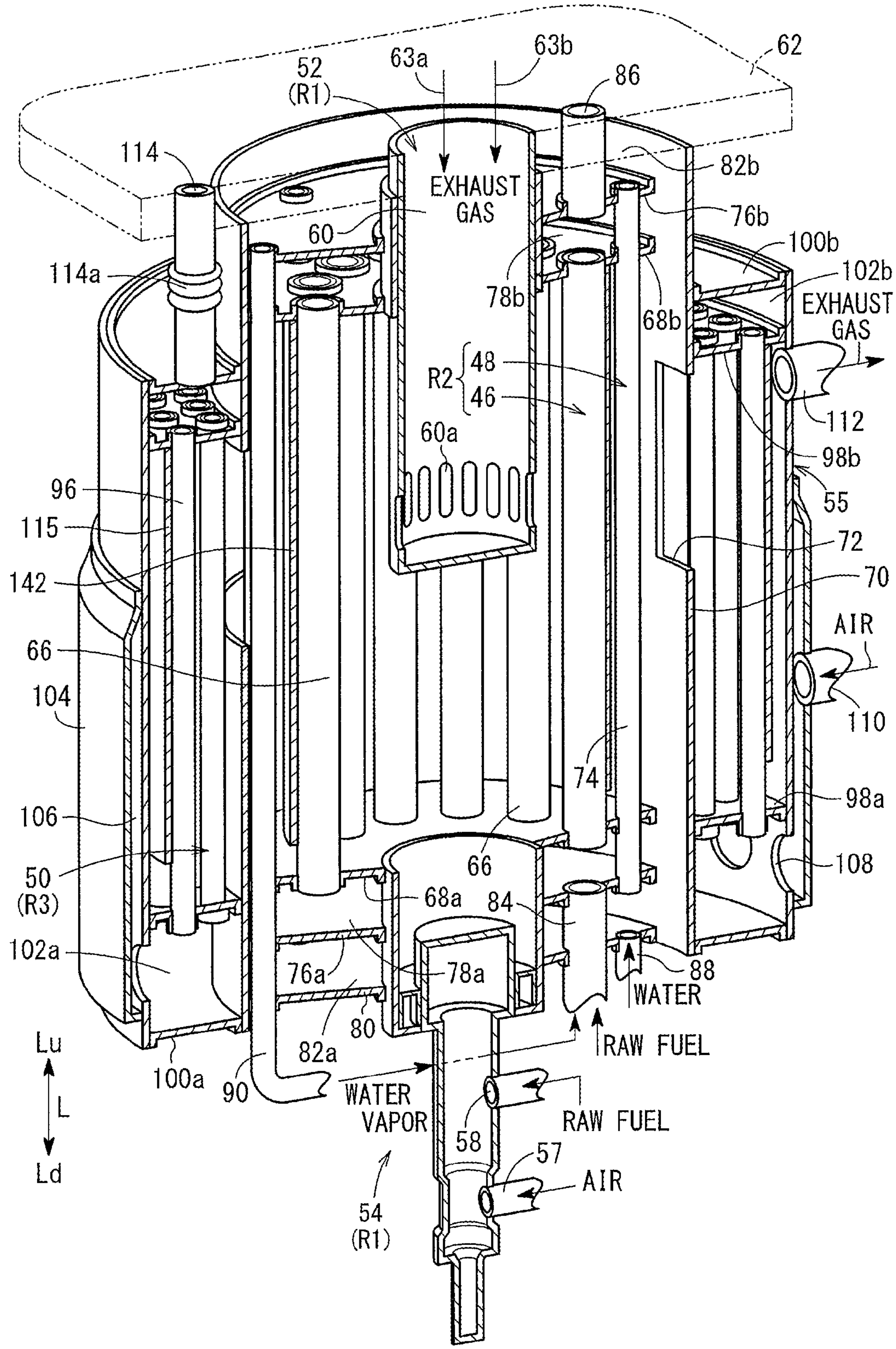
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FIG. 13

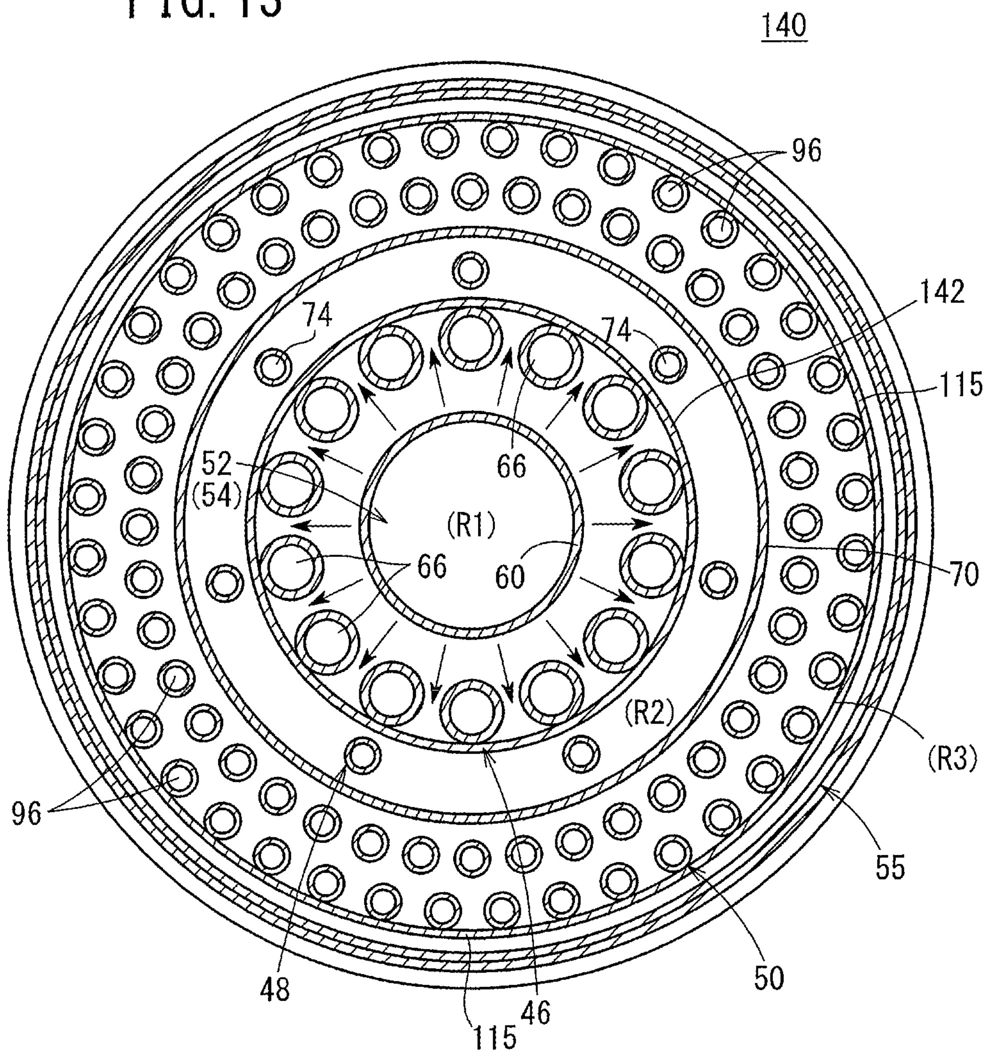

FIG. 14

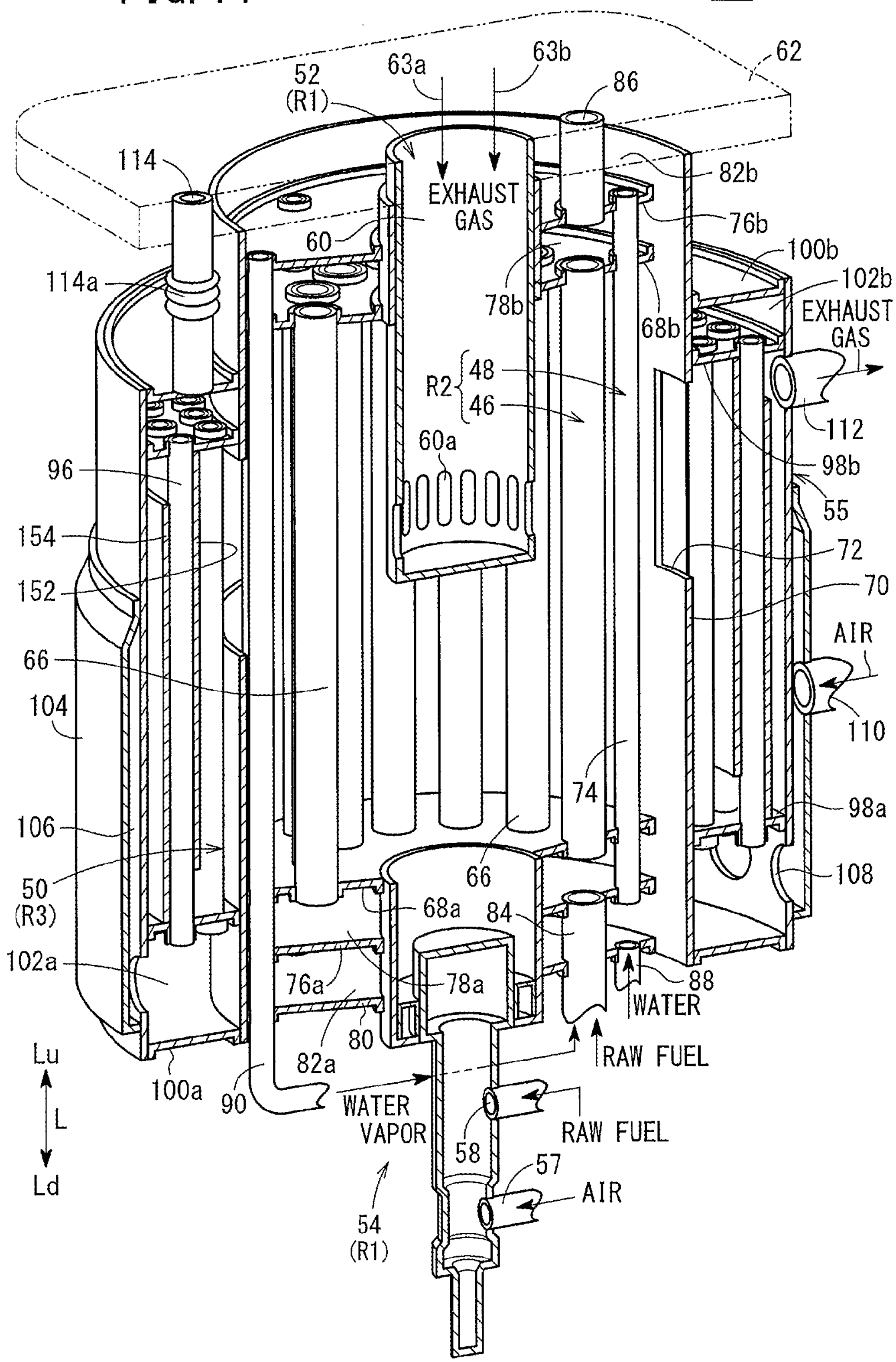
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FIG. 15

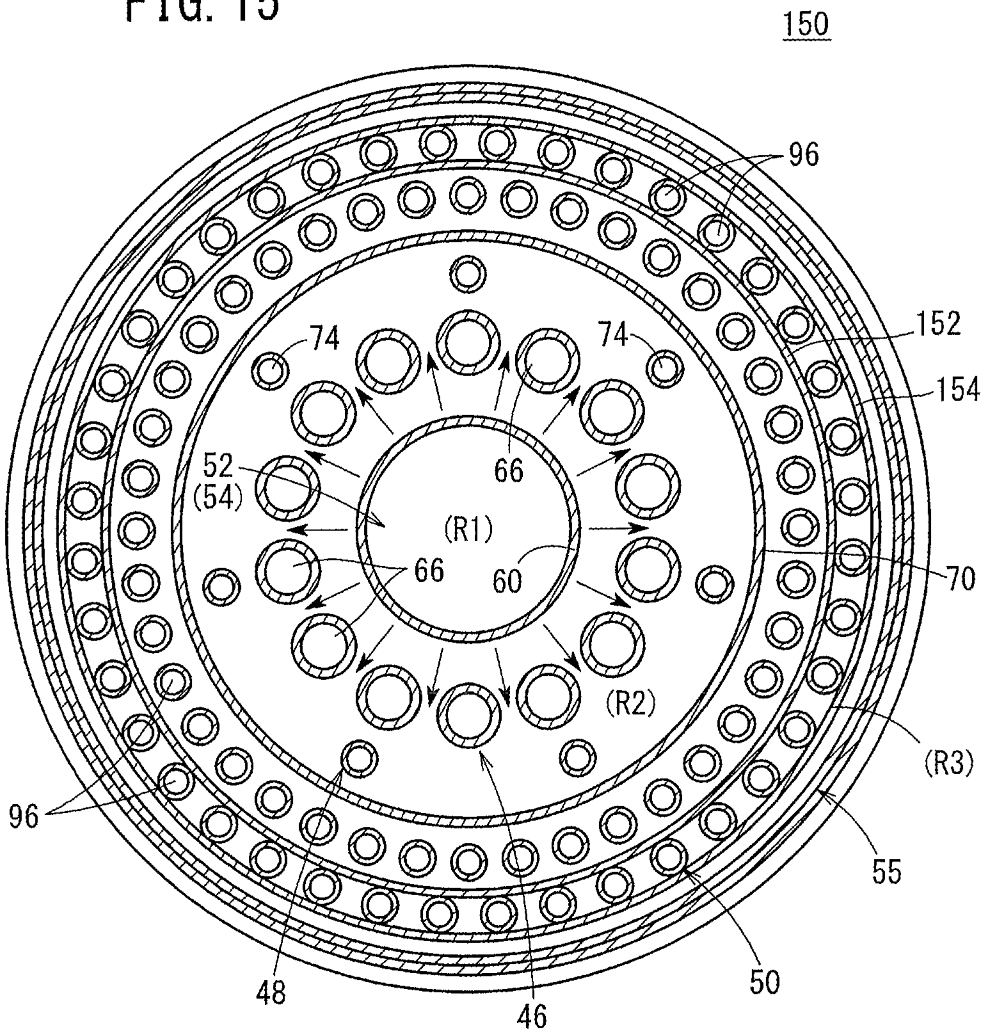


FIG. 16

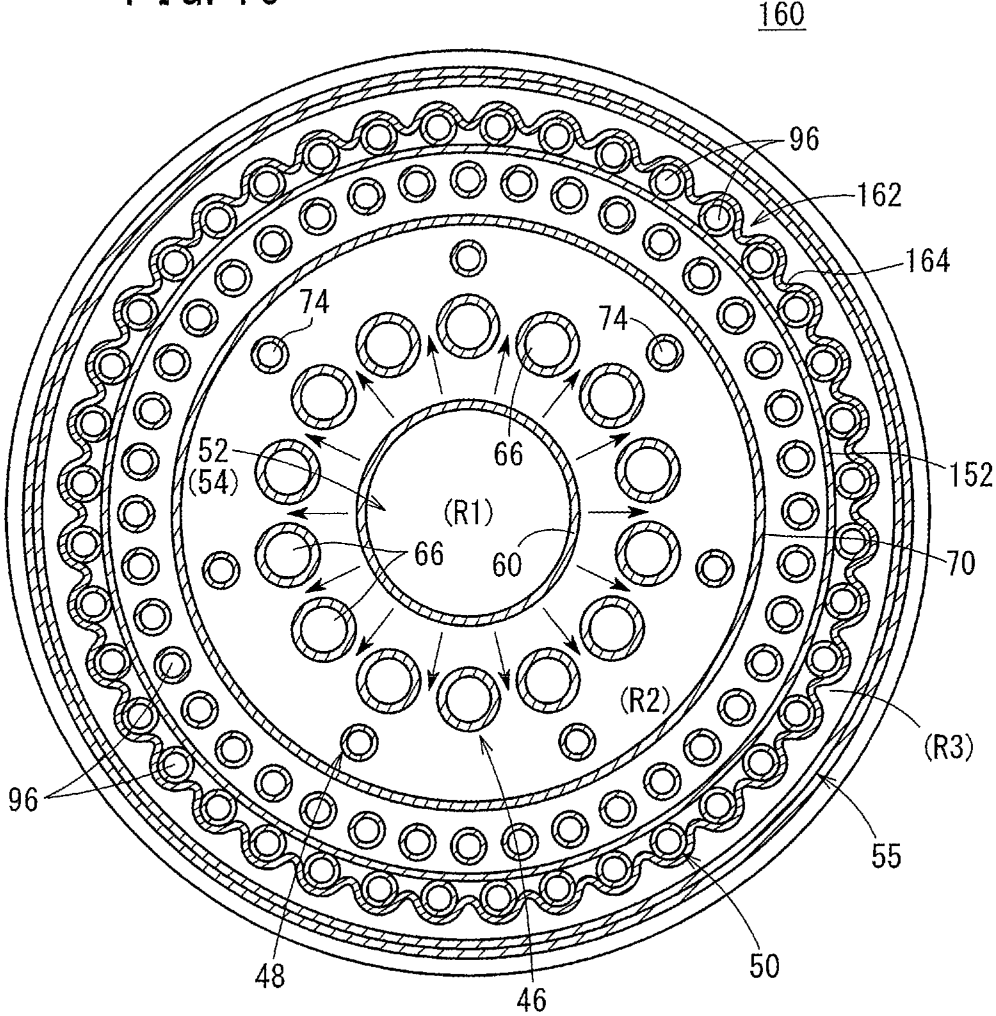
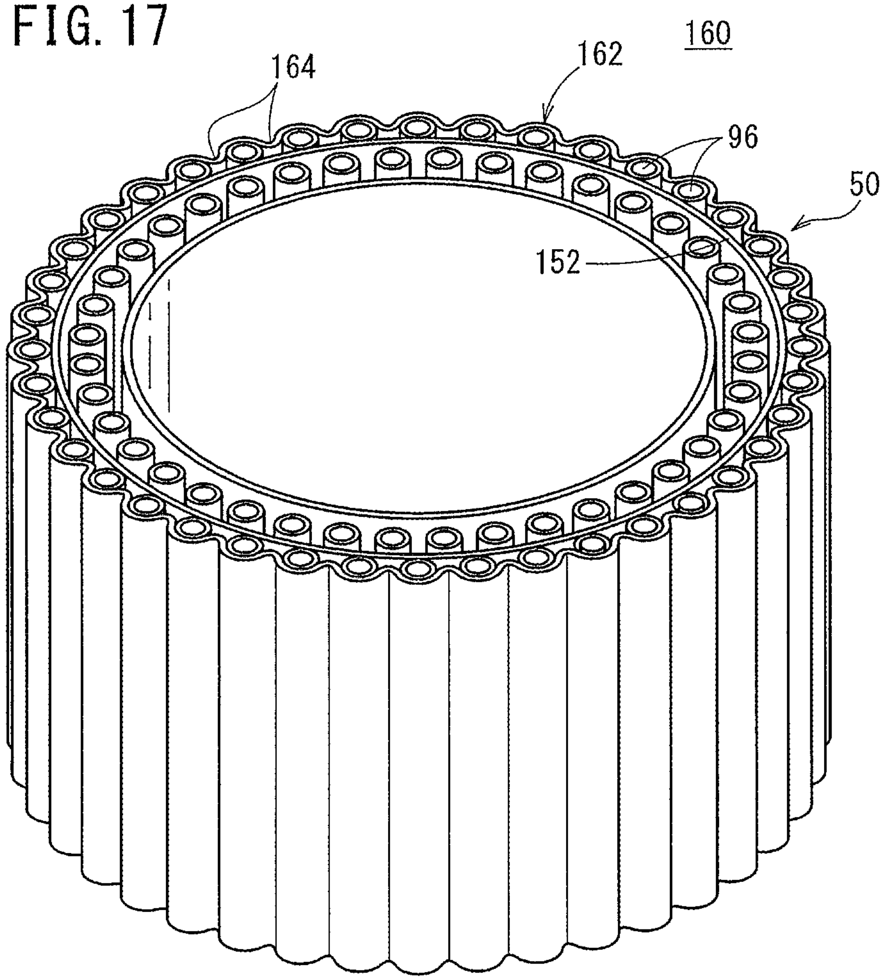
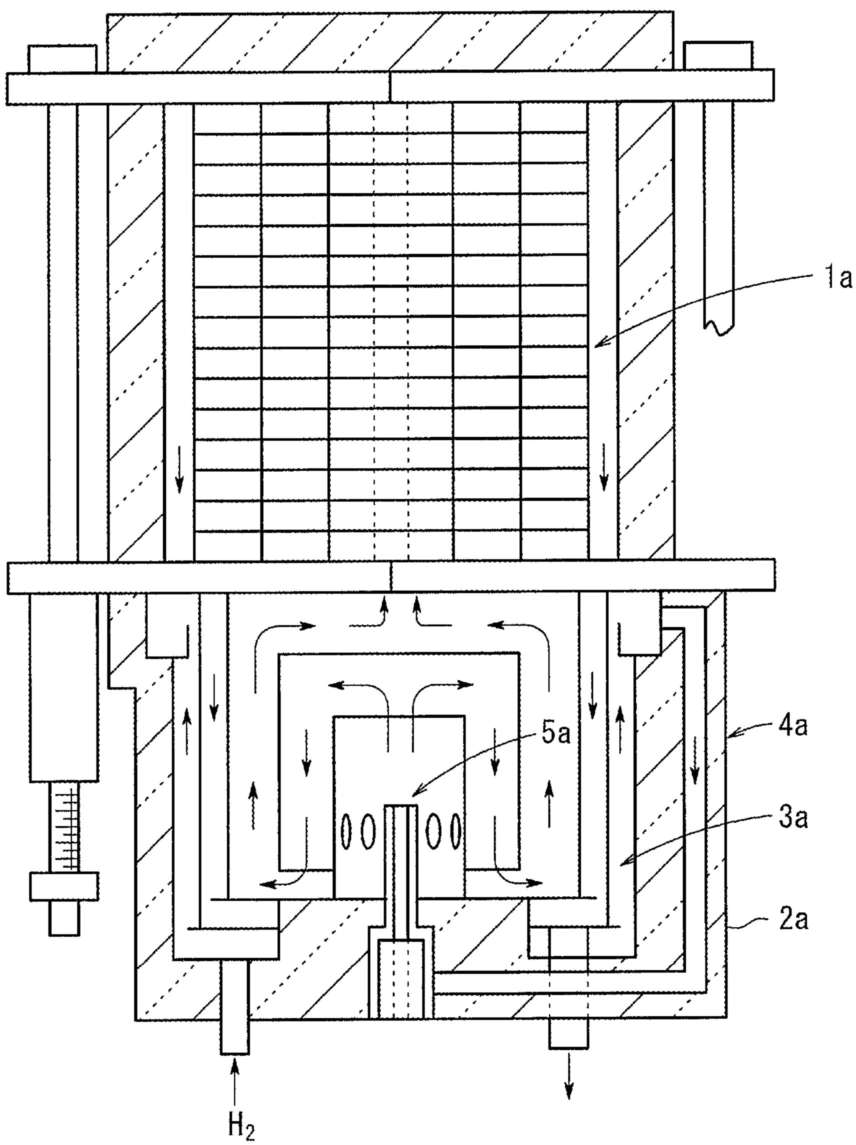


FIG. 17



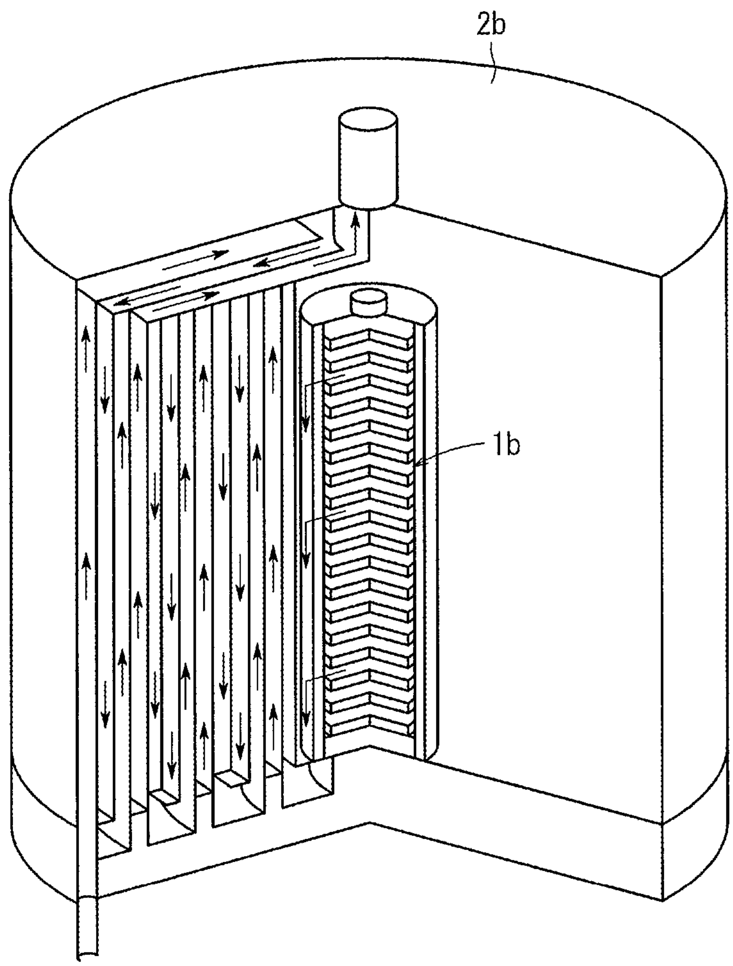
PRIOR ART

FIG. 18



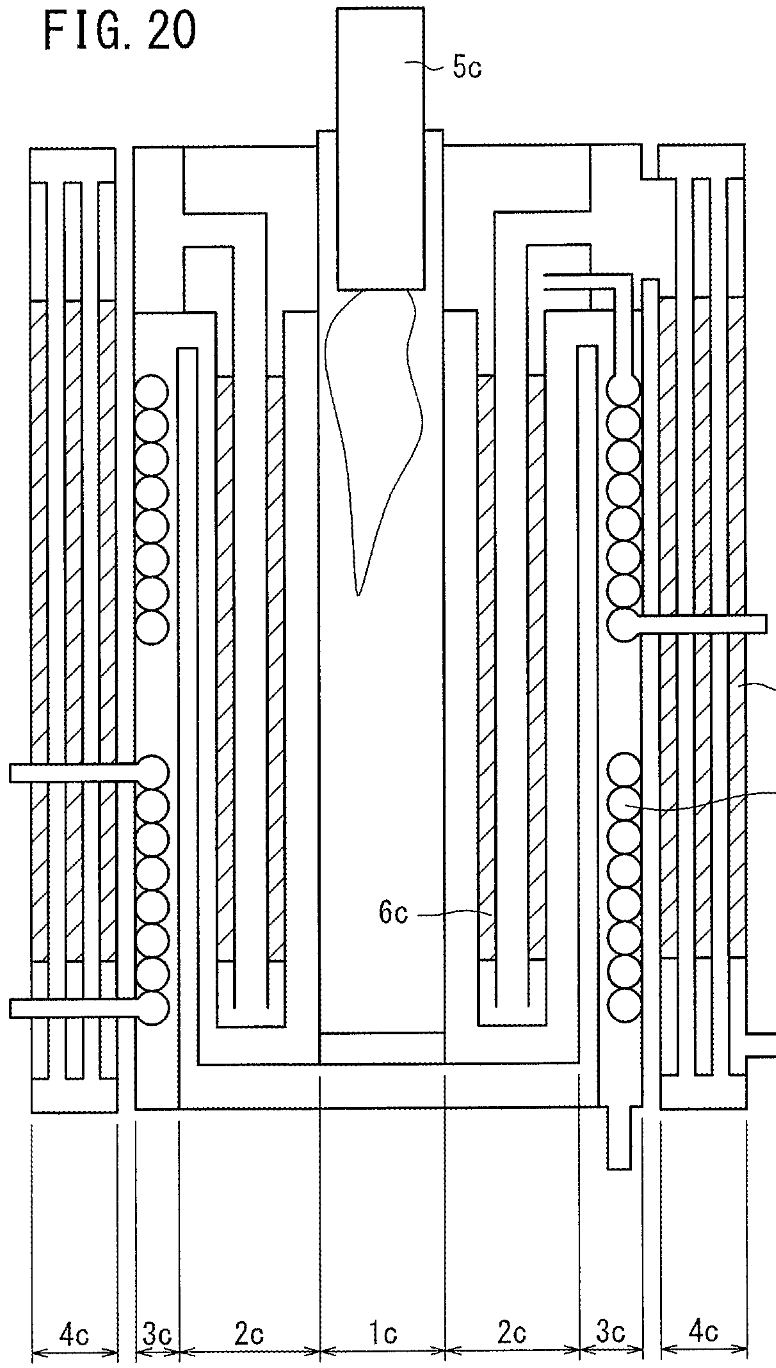
PRIOR ART

FIG. 19



PRIOR ART

FIG. 20



FUEL CELL MODULE

TECHNICAL FIELD

The present invention relates to a fuel cell module including a fuel cell stack formed by stacking a plurality of fuel cells for generating electricity by electrochemical reactions of a fuel gas and an oxygen-containing gas.

BACKGROUND ART

Typically, a solid oxide fuel cell (SOFC) employs a solid electrolyte of ion-conductive solid oxide such as stabilized zirconia. The solid electrolyte is interposed between an anode and a cathode to form an electrolyte electrode assembly (hereinafter also referred to as MEA). The electrolyte electrode assembly is sandwiched between separators (bipolar plates). In use, generally, predetermined numbers of the electrolyte electrode assemblies and the separators are stacked together to form a fuel cell stack.

As a system including this type of fuel cell stack, for example, a fuel cell battery disclosed in Japanese Laid-Open Patent Publication No. 2001-236980 (hereinafter referred to as the conventional technique 1) is known. As shown in FIG. **18**, the fuel cell battery includes a fuel cell stack **1***a*, and a heat insulating sleeve **2***a* is provided at one end of the fuel cell stack **1***a*. A reaction device **4***a* is provided in the heat insulating sleeve **2***a*. The reaction device **4***a* includes a heat exchanger **3***a*.

In the reaction device **4***a*, as a treatment of liquid fuel, partial oxidation reforming which does not use water is performed. After the liquid fuel is evaporated by an exhaust gas, the liquid fuel passes through a feeding point **5***a* which is part of the heat exchanger **3***a*. The fuel contacts an oxygen carrier gas heated by the exhaust gas thereby to induce partial oxidation reforming, and then, the fuel is supplied to the fuel cell stack **1***a*.

Further, as shown in FIG. **19**, a solid oxide fuel cell disclosed in Japanese Laid-Open Patent Publication No. 2010-504607 (PCT) (hereinafter referred to as the conventional technique 2) has a heat exchanger **2***b* including a cell core **1***b*. The heat exchanger **2***b* heats the cathode air utilizing waste heat.

Further, as shown in FIG. **20**, a fuel cell system disclosed in Japanese Laid-Open Patent Publication No. 2004-288434 (hereinafter referred to as the conventional technique 3) includes a first area **1***c* having a circular cylindrical shape extending vertically, and an annular second area **2***c* around the first area **1***c*, an annular third area **3***c* around the second area **2***c*, and an annular fourth area **4***c* around the third area **3***c*.

A burner **5***c* is provided in the first area **1***c*, and a reforming pipe **6***c* is provided in the second area **2***c*. A water evaporator **7***c* is provided in the third area **3***c*, and a CO shift converter **8***c* is provided in the fourth area **4***c*.

SUMMARY OF INVENTION

In the conventional technique 1, at the time of reforming by partial oxidation in the reaction device **4***a*, heat of the exhaust gas is used for heating the liquid fuel and the oxygen carrier gas. Therefore, the quantity of heat for raising the temperature of the oxygen-containing gas supplied to the fuel cell stack **1***a* tends to be insufficient, and the efficiency is low. Further, since the heat exchanger **3***a* only heats the outer wall by the exhaust gas, a desired quantity of heat cannot be obtained. Further, non-uniform flow tends to be produced easily in the exhaust gas.

Further, in the conventional technique 2, in order to increase heat efficiency, long flow channels are adopted to have a sufficient heat transmission area. Therefore, considerably high pressure losses tend to occur. Moreover, since the heat exchanger **2***b* only heats the outer wall by the exhaust gas, a desired quantity of heat cannot be obtained. Further, non-uniform flow tends to be produced easily in the exhaust gas.

Further, in the conventional technique 3, radiation of the heat from the central area having the highest temperature is suppressed using heat insulation material (partition wall). Therefore, heat cannot be recovered, and the efficiency is low. Further, since the combustion gas flows along the partition wall, the effective quantity of heat cannot be obtained.

The present invention has been made to solve the problems of this type, and an object of the present invention is to provide a fuel cell module having simple and compact structure in which it is possible to achieve improvement in the heat efficiency and facilitation of thermally self-sustaining operation, and also it is possible to reliably suppress non-uniform flow of a combustion gas, whereby improvement in the heat exchange efficiency can be achieved suitably.

The present invention relates to a fuel cell module including a fuel cell stack formed by stacking a plurality of fuel cells for generating electricity by electrochemical reactions of a fuel gas and an oxygen-containing gas, a reformer for reforming a mixed gas of water vapor and a raw fuel chiefly containing hydrocarbon to produce the fuel gas supplied to the fuel cell stack, an evaporator for evaporating water, and supplying the water vapor to the reformer, a heat exchanger for raising the temperature of the oxygen-containing gas by heat exchange with a combustion gas, and supplying the oxygen-containing gas to the fuel cell stack, an exhaust gas combustor for combusting the fuel gas discharged from the fuel cell stack as a fuel exhaust gas and the oxygen-containing gas discharged from the fuel cell stack as an oxygen-containing exhaust gas to produce the combustion gas, and a start-up combustor for combusting the raw fuel and the oxygen-containing gas to produce the combustion gas.

The fuel cell module includes a first area where the exhaust gas combustor and the start-up combustor are provided, an annular second area around the first area and where the reformer and the evaporator are provided, and an annular third area around the second area and where the heat exchanger is provided.

In the fuel cell module, the heat exchanger includes an annular oxygen-containing gas supply chamber to which the oxygen-containing gas is supplied, an annular oxygen-containing gas discharge chamber to which the heated oxygen-containing gas is discharged, a plurality of heat exchange pipes each having one end connected to the oxygen-containing gas supply chamber and another end connected to the oxygen-containing gas discharge chamber, and a combustion gas channel for supplying the combustion gas to spaces between the heat exchange pipes. A circumscribed non-uniform flow suppression plate is provided along the minimum circumscribed circle which is tangent to outer surfaces of the plurality of heat exchange pipes.

In the present invention, the first area including the exhaust gas combustor and the start-up combustor is centrally-located. The annular second area is successively provided around the first area, and the annular third area is then provided around the second area. The reformer and the evaporator are provided in the second area, and the heat exchanger is provided in the third area.

In the structure, heat waste and heat radiation are suppressed suitably. Thus, improvement in the heat efficiency is achieved, and thermally self-sustaining operation is facilitated. Further, simple and compact structure is achieved in the entire fuel cell module. The thermally self-sustaining operation herein means operation where the operating temperature of the fuel cell is maintained using only heat energy generated by the fuel cell itself, without supplying additional heat from the outside.

Further, in the heat exchanger, the annular oxygen-containing gas supply chamber, the annular oxygen-containing gas discharge chamber, and the heat exchange pipes are provided as basic structure. Thus, simple structure is achieved easily. Accordingly, the production cost is reduced effectively. Further, by changing the volumes of the oxygen-containing gas supply chamber and the oxygen-containing gas discharge chamber, the length, the diameter, and the number of the pipes, a desired operation can be achieved depending on various operating conditions, and a wider variety of designs become available.

Still further, the circumscribed non-uniform flow suppression plate is provided along the minimum circumscribed circle which is tangent to outer surfaces of the plurality of heat exchange pipes. Thus, by the guidance of the circumscribed non-uniform flow suppression plate, the combustion gas flows along the outer surfaces of the heat exchange pipes suitably. Thus, non-uniform flow and blow-through of the combustion gas are suppressed suitably, and the channel of the combustion gas can be sufficiently long. Accordingly, the quantity of the heat passed from the combustion gas to the oxygen-containing gas is increased, and improvement in the heat exchange efficiency is achieved suitably.

The above and other objects features and advantages of the present invention will become more apparent from the following description when taken in conjunction with the accompanying drawings in which preferred embodiments of the present invention are shown by way of illustrative example.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a diagram schematically showing structure of a fuel cell system including a fuel cell module according to a first embodiment of the present invention;

FIG. **2** is a perspective view showing FC peripheral equipment of the fuel cell module;

FIG. **3** is a cross sectional view showing the FC peripheral equipment;

FIG. **4** is a perspective view with partial omission showing the FC peripheral equipment;

FIG. **5** is an exploded perspective view showing main components of the FC peripheral equipment;

FIG. **6** is a cross sectional plan view showing the FC peripheral equipment;

FIG. **7** is a view showing an evaporation return pipe of the FC peripheral equipment;

FIG. **8** is a perspective view with partial omission showing a fuel cell module according to a second embodiment of the present invention;

FIG. **9** is a cross sectional view showing the fuel cell module;

FIG. **10** is a cross sectional plan view showing the fuel cell module;

FIG. **11** is a cross sectional view showing a fuel cell module according to a third embodiment of the present invention;

FIG. **12** is a perspective view with partial omission showing the fuel cell module;

FIG. **13** is a cross sectional plan view showing the fuel cell module;

FIG. **14** is a perspective view with partial omission showing a fuel cell module according to a fourth embodiment of the present invention;

FIG. **15** is a cross sectional plan view showing the fuel cell module;

FIG. **16** is a cross sectional plan view showing a fuel cell module according to a fifth embodiment of the present invention;

FIG. **17** is a perspective view showing main components of a heat exchanger of the fuel cell module;

FIG. **18** is a view schematically showing a fuel cell battery disclosed in a conventional technique 1;

FIG. **19** is a perspective view with partial cutout showing a solid oxide fuel cell disclosed in a conventional technique 2; and

FIG. **20** is a view schematically showing a fuel cell system disclosed in a conventional technique 3.

DESCRIPTION OF EMBODIMENTS

As shown in FIG. **1**, a fuel cell system **10** includes a fuel cell module **12** according to a first embodiment of the present invention, and the fuel cell system **10** is used in various applications, including stationary and mobile applications. For example, the fuel cell system **10** is mounted on a vehicle.

The fuel cell system **10** includes the fuel cell module (SOFC module) **12** for generating electrical energy in power generation by electrochemical reactions of a fuel gas (a gas produced by mixing a hydrogen gas, methane, and carbon monoxide) and an oxygen-containing gas (air), a raw fuel supply apparatus (including a fuel gas pump) **14** for supplying a raw fuel (e.g., city gas) to the fuel cell module **12**, an oxygen-containing gas supply apparatus (including an air pump) **16** for supplying the oxygen-containing gas to the fuel cell module **12**, a water supply apparatus (including a water pump) **18** for supplying water to the fuel cell module **12**, and a control device **20** for controlling the amount of electrical energy generated in the fuel cell module **12**.

The fuel cell module **12** includes a solid oxide fuel cell stack **24** formed by stacking a plurality of solid oxide fuel cells **22** in a vertical direction (or horizontal direction). The fuel cell **22** includes an electrolyte electrode assembly (MEA) **32**. The electrolyte electrode assembly **32** includes a cathode **28**, an anode **30**, and an electrolyte **26** interposed between the cathode **28** and the anode **30**. For example, the electrolyte **26** is made of ion-conductive solid oxide such as stabilized zirconia.

A cathode side separator **34** and an anode side separator **36** are provided on both sides of the electrolyte electrode assembly **32**. An oxygen-containing gas flow field **38** for supplying the oxygen-containing gas to the cathode **28** is formed in the cathode side separator **34**, and a fuel gas flow field **40** for supplying the fuel gas to the anode **30** is formed in the anode side separator **36**. As the fuel cell **22**, various types of conventional SOFCs can be adopted.

The operating temperature of the fuel cell **22** is high, that is, several hundred ° C. Methane in the fuel gas is reformed at the anode **30** to obtain hydrogen and CO, and the hydrogen and CO are supplied to a portion of the electrolyte **26** adjacent to the anode **30**.

An oxygen-containing gas supply passage **42***a*, an oxygen-containing gas discharge passage **42***b*, a fuel gas supply passage **44***a*, and a fuel gas discharge passage **44***b* extend through the fuel cell stack **24**. The oxygen-containing gas supply passage **42***a* is connected to an inlet of each oxygen-containing gas flow field **38**, the oxygen-containing gas discharge passage **42***b* is connected to an outlet of each oxygen-containing gas flow field **38**, the fuel gas supply passage **44**a is connected to an inlet of each fuel gas flow field **40**, and the fuel gas discharge passage **44**b is connected to an outlet of each fuel gas flow field **40**.

The fuel cell module **12** includes a reformer **46** for reforming a mixed gas of water vapor and a raw fuel chiefly containing hydrocarbon (e.g., city gas) to produce a fuel gas supplied to the fuel cell stack **24**, an evaporator **48** for evaporating water and supplying the water vapor to the reformer **46**, a heat exchanger **50** for raising the temperature of the oxygen-containing gas by heat exchange with a combustion gas, and supplying the oxygen-containing gas to the fuel cell stack **24**, an exhaust gas combustor **52** for combusting the fuel gas discharged from the fuel cell stack **24** as a fuel exhaust gas and the oxygen-containing gas discharged from the fuel cell stack **24** as an oxygen-containing exhaust gas to produce the combustion gas, and a start-up combustor **54** for combusting the raw fuel and the oxygen-containing gas to produce the combustion gas.

Basically, the fuel cell module **12** is made up of the fuel cell stack **24** and FC (fuel cell) peripheral equipment (BOP) **56** (see FIGS. **1** and **2**). The FC peripheral equipment **56** includes the reformer **46**, the evaporator **48**, the heat exchanger **50**, the exhaust gas combustor **52**, and the start-up combustor **54**.

As shown in FIGS. **3** to **5**, the FC peripheral equipment **56** includes a first area R**1** where the exhaust gas combustor **52** and the start-up combustor **54** are provided, an annular second area R**2** formed around the first area R**1** and where the reformer **46** and the evaporator **48** are provided, an annular third area R**3** formed around the second area R**2** and where the heat exchanger **50** is provided. A cylindrical outer member **55** constituting an outer wall is provided on the outer peripheral side of the third area R**3**.

The start-up combustor **54** includes an air supply pipe **57** and a raw fuel supply pipe **58**. The start-up combustor **54** has an ejector function, and generates negative pressure in the raw fuel supply pipe **58** by the flow of the air supplied from the air supply pipe **57** for sucking the raw fuel.

The exhaust gas combustor **52** is spaced away from the start-up combustor **54**, and includes a combustion cup **60** formed in a shape of a cylinder having a bottom. A plurality of holes (e.g., circular holes or rectangular holes) **60**a are formed along the outer circumference of the marginal end of the combustion cup **60** on the bottom side. A stack attachment plate **62** is engaged with the other end of the combustion cup **60** on the opening side. The fuel cell stack **24** is attached to the stack attachment plate **62**.

One end of an oxygen-containing exhaust gas channel **63**a and one end of a fuel exhaust gas channel **63**b are provided at the combustion cup **60**. The combustion gas is produced inside the combustion cup **60** by combustion reaction of the fuel gas (more specifically, fuel exhaust gas) and the oxygen-containing gas (more specifically, oxygen-containing exhaust gas).

As shown in FIG. **1**, the other end of the oxygen-containing exhaust gas channel **63**a is connected to the oxygen-containing gas discharge passage **42**b of the fuel cell stack **24**, and the other end of the fuel exhaust gas channel **63**b is connected to the fuel gas discharge passage **44**b of the fuel cell stack **24**.

As shown in FIGS. **3** to **5**, the reformer **46** is a preliminary reformer for reforming higher hydrocarbon (C_{2+}) such as ethane (C_2H_6), propane (C_2H_8), and butane (C_4H_{10}) in the city gas (raw fuel) to produce the fuel gas chiefly containing methane (CH_4), hydrogen, and CO by steam reforming. The operating temperature of the reformer **46** is set at several hundred ° C.

The reformer **46** includes a plurality of reforming pipes (heat transmission pipes) **66** provided around the exhaust gas combustor **52** and the start-up combustor **54**. Each of the reforming pipes **66** is filled with reforming catalyst pellets (not shown). Each of the reforming pipes **66** has one end (lower end) fixed to a first lower ring member **68**a, and the other end (upper end) fixed to a first upper ring member **68**b.

The outer circumferential portions of the first lower ring member **68**a and the first upper ring member **68**b are fixed to the inner circumferential portion of a cylindrical member **70** by welding or the like. The inner circumferential portions of the first lower ring member **68**a and the first upper ring member **68**b are fixed to the outer circumferential portions of the exhaust gas combustor **52** and the start-up combustor **54** by welding or the like. The cylindrical member **70** extends in an axial direction indicated by an arrow L, and an end of the cylindrical member **70** adjacent to the fuel cell stack **24** is fixed to the stack attachment plate **62**. A plurality of openings **72** are formed in the outer circumference of the cylindrical member **70** in a circumferential direction at predetermined height positions.

The evaporator **48** has evaporation pipes (heat transmission pipes) **74** provided adjacent to, and outside the reforming pipes **66** of the reformer **46**. As shown in FIG. **6**, the reforming pipes **66** are arranged at equal intervals on a virtual circle, concentrically around the first area R**1**. The evaporation pipes **74** are arranged at equal intervals on a virtual circle, concentrically around the first area R**1**. The number of the evaporation pipes **74** is half of the number of the reforming pipes **66**. The evaporation pipes **74** are positioned on the back side of every other position of the reforming pipe **66** (i.e., at positions spaced away from the center of the first area R**1**).

As shown in FIGS. **3** and **4**, each of the evaporation pipes **74** has one end (lower end) which is fixed to a second lower ring member **76**a by welding or the like, and the other end (upper end) which is fixed to a second upper ring member **76**b by welding or the like. The outer circumferential portions of the second lower ring member **76**a and the second upper ring member **76**b are fixed to the inner circumferential portion of the cylindrical member **70** by welding or the like. The inner circumferential portions of the second lower ring member **76**a and the second upper ring member **76**b are fixed to the outer circumferential portions of the exhaust gas combustor **52** and the start-up combustor **54** by welding or the like.

The second lower ring member **76**a is positioned below the first lower ring member **68**a (i.e., outside the first lower ring member **68**a in the axial direction), and the second upper ring member **76**b is positioned above the first upper ring member **68**b (i.e., outside the first upper ring member **68**b in the axial direction).

An annular mixed gas supply chamber **78**a is formed between the first lower ring member **68**a and the second lower ring member **76**a, and a mixed gas of raw fuel and water vapor is supplied to the mixed gas supply chamber **78**a. Further, an annular fuel gas discharge chamber **78**b is formed between the first upper ring member **68**b and the second upper ring member **76**b, and the produced fuel gas (reformed gas) is discharged to the fuel gas discharge chamber **78**b. Both ends of each of the reforming pipes **66** are opened to the mixed gas supply chamber **78**a and the fuel gas discharge chamber **78**b.

A ring shaped end ring member **80** is fixed to an end of the cylindrical member **70** on the start-up combustor **54** side by welding or the like. An annular water supply chamber **82**a is formed between the end ring member **80** and the second lower ring member **76**a, and water is supplied to the water supply chamber **82**a. An annular water vapor discharge chamber **82**b is formed between the second upper ring member **76**b and the stack attachment plate **62**, and water vapor is discharged to the water vapor discharge chamber **82***b*. Both ends of each of the evaporation pipes **74** are opened to the water supply chamber **82***a* and the water vapor discharge chamber **82***b*.

The fuel gas discharge chamber **78***b* and the water vapor discharge chamber **82***b* are provided in a double deck manner, and the fuel gas discharge chamber **78***b* is provided on the inner side with respect to the water vapor discharge chamber **82***b* (i.e., below the water vapor discharge chamber **82***b*). The mixed gas supply chamber **78***a* and the water supply chamber **82***a* are provided in a double deck manner, and the mixed gas supply chamber **78***a* is provided on the inner side with respect to the water supply chamber **82***a* (i.e., above the water supply chamber **82***a*).

A raw fuel supply channel **84** is opened to the mixed gas supply chamber **78***a*, and an evaporation return pipe **90** described later is connected to a position in the middle of the raw fuel supply channel **84** (see FIG. **1**). The raw fuel supply channel **84** has an ejector function, and generates negative pressure by the flow of the raw fuel for sucking the water vapor.

The raw fuel supply channel **84** is fixed to the second lower ring member **76***a* and the end ring member **80** by welding or the like. One end of a fuel gas channel **86** is connected to the fuel gas discharge chamber **78***b*, and the other end of the fuel gas channel **86** is connected to the fuel gas supply passage **44***a* of the fuel cell stack **24** (see FIG. **1**). The fuel gas channel **86** is fixed to the second upper ring member **76***b* by welding or the like, and extends through the stack attachment plate **62** (see FIG. **2**).

A water channel **88** is connected to the water supply chamber **82***a*. The water channel **88** is fixed to the end ring member **80** by welding or the like. One end of the evaporation return pipe **90** formed by at least one evaporation pipe **74** is provided in the water vapor discharge chamber **82***b*, and the other end of the evaporation return pipe **90** is connected to a position in the middle of the raw fuel supply channel **84** (see FIG. **1**).

As shown in FIG. **7**, the evaporation return pipe **90** has dual pipe structure **92** in a portion thereof passing through the mixed gas supply chamber **78***a* and the water supply chamber **82***a*. The dual pipe structure **92** includes an outer pipe **94**. The outer pipe **94** surrounds the evaporation return pipe **90**, and the outer pipe **94** is positioned coaxially with the evaporation return pipe **90**. The outer pipe **94** is fixed to the first lower ring member **68***a*, the second lower ring member **76***a*, and the end ring member **80** by welding or the like, and extends in the direction indicated by an arrow L. A gap is provided between the outer circumference of the evaporation return pipe **90** and the inner circumference of the outer pipe **94**. This gap may not be provided.

The evaporation return pipe **90** may have dual pipe structure **92***a* in a portion thereof passing through the fuel gas discharge chamber **78***b*. The dual pipe structure **92***a* includes an outer pipe **94***a*. The outer pipe **94***a* surrounds the evaporation return pipe **90**, and the outer pipe **94***a* is positioned coaxially with the evaporation return pipe **90**. The outer pipe **94***a* is fixed to the first upper ring member **68***b* and the second upper ring member **76***b* by welding or the like, and extends in the direction indicated by the arrow L. A gap is formed between the outer circumference of the evaporation return pipe **90** and the inner circumference of the outer pipe **94***a* as necessary. The lower end of the outer pipe **94***a* is not welded to the first upper ring member **68***b*.

As shown in FIGS. **3** and **4**, the heat exchanger **50** includes a plurality of heat exchange pipes (heat transmission pipes) **96** which are provided along and around the outer circumference of the cylindrical member **70**. As shown in FIG. **6**, a plurality of the heat exchange pipes **96** are arranged on each of two virtual circles positioned concentrically around the center of the first area R**1**. Each of the heat exchange pipes **96** has one end (lower end) fixed to a lower ring member **98***a*, and the other end (upper end) fixed to an upper ring member **98***b*.

A lower end ring member **100***a* is provided below the lower ring member **98***a*, and an upper end ring member **100***b* is provided above the upper ring member **98***b*. The lower end ring member **100***a* and the upper end ring member **100***b* are fixed to the outer circumference of the cylindrical member **70** and the inner circumference of the outer member **55** by welding or the like.

An annular oxygen-containing gas supply chamber **102***a* to which the oxygen-containing gas is supplied is formed between the lower ring member **98***a* and the lower end ring member **100***a*. An annular oxygen-containing gas discharge chamber **102***b* is formed between the upper ring member **98***b* and the upper end ring member **100***b*. The heated oxygen-containing gas is discharged to the oxygen-containing gas discharge chamber **102***b*. Both ends of each of the heat exchange pipes **96** are fixed to the lower ring member **98***a* and the upper ring member **98***b* by welding or the like, and opened to the oxygen-containing gas supply chamber **102***a* and the oxygen-containing gas discharge chamber **102***b*.

The mixed gas supply chamber **78***a* and the water supply chamber **82***a* are placed on the radially inward side relative to the inner circumference of the oxygen-containing gas supply chamber **102***a*. The oxygen-containing gas discharge chamber **102***b* is provided outside the fuel gas discharge chamber **78***b* at a position offset downward from the fuel gas discharge chamber **78***b*.

A cylindrical cover member **104** is provided on the outer circumferential portion of the outer member **55**. The center position of the cylindrical cover member **104** is shifted downward. Both of upper and lower ends (both of axial ends) of the cover member **104** are fixed to the outer member **55** by welding or the like, and a heat recovery area (chamber) **106** is formed between the cover member **104** and the outer circumferential portion of the outer member **55**.

A plurality of holes **108** are formed circumferentially in a lower marginal end portion of the outer member **55** of the oxygen-containing gas supply chamber **102***a*, and the oxygen-containing gas supply chamber **102***a* communicates with the heat recovery area **106** through the holes **108**. An oxygen-containing gas supply pipe **110** communicating with the heat recovery area **106** is connected to the cover member **104**. An exhaust gas pipe **112** communicating with the third area R**3** is connected to an upper portion of the outer member **55**.

For example, one end of each of two oxygen-containing gas pipes **114** is provided in the oxygen-containing gas discharge chamber **102***b*. Each of the oxygen-containing gas pipes **114** has a stretchable member such as a bellows **114***a* between the upper end ring member **100***b* and the stack attachment plate **62**. The other end of each of the oxygen-containing gas pipes **114** extends through the stack attachment plate **62**, and is connected to the oxygen-containing gas supply passage **42***a* of the fuel cell stack **24** (see FIG. **1**).

In the first embodiment, as shown in FIGS. **3** to **6**, a circumscribed non-uniform flow suppression plate **115** is provided in the third area R**3** where the heat exchanger **50** is provided. The circumscribed non-uniform flow suppression plate **115** has a cylindrical shape. As shown in FIG. **6**, the circumscribed non-uniform flow suppression plate **115** is provided along the minimum circumscribed circle which is tangent to the outer surfaces of the plurality of heat exchange pipes **96** arranged along the outer virtual circle. For example, the circumscribed non-uniform flow suppression plate **115** is fixed to the heat exchange pipes **96** by welding or the like.

As shown in FIGS. **3** and **7**, the circumscribed non-uniform flow suppression plate **115** is made of a thin metal plate, and positioned on a side closer to the exhaust gas combustor **52** in the pipe length direction, indicated by an arrow L, of the heat exchange pipes **96**. Specifically, the upper end of the circumscribed non-uniform flow suppression plate **115** is fixed to the upper ring member **98***b*, and the lower end of the circumscribed non-uniform flow suppression plate **115** is spaced upward from the lower ring member **98***a* by a predetermined distance h. The circumscribed non-uniform flow suppression plate **115** may be provided as closely as possible to the heat exchange pipes **96**.

As shown in FIG. **3**, a first combustion gas channel **116***a* as a passage of the combustion gas is formed in the first area R**1**, and a second combustion gas channel **116***b* as a passage of the combustion gas that has passed through the holes **60***a* is formed in the second area R**2**. A third combustion gas channel **116***c* as a passage of the combustion gas that has passed through the openings **72** is formed in the third area R**3**. Further, a fourth combustion gas channel **116***d* is formed as a passage of the combustion gas after the exhaust gas pipe **112**.

The second combustion gas channel **116***b* forms the reformer **46** and the evaporator **48**, and the third combustion gas channel **116***c* forms the heat exchanger **50**. The third combustion gas channel **116***c* has a bent shape, in which gas first flows downward in a direction indicated by an arrow Ld by the circumscribed non-uniform flow suppression plate **115**, next flows between the lower end of the circumscribed non-uniform flow suppression plate **115** and the lower ring member **98***a*, and then turns up and flows upward in a direction indicated by an arrow Lu.

As shown in FIG. **1**, the raw fuel supply apparatus **14** includes a raw fuel channel **118**. The raw fuel channel **118** is branched into the raw fuel supply channel **84** and the raw fuel supply pipe **58** through a raw fuel regulator valve **120**. A desulfurizer **122** for removing sulfur compounds in the city gas (raw fuel) is provided in the raw fuel supply channel **84**.

The oxygen-containing gas supply apparatus **16** includes an oxygen-containing gas channel **124**. The oxygen-containing gas channel **124** is branched into the oxygen-containing gas supply pipe **110** and the air supply pipe **57** through an oxygen-containing gas regulator valve **126**. The water supply apparatus **18** is connected to the evaporator **48** through the water channel **88**.

Operation of the fuel cell system **10** will be described below.

At the time of starting operation of the fuel cell system **10**, the air (oxygen-containing gas) and the raw fuel are supplied to the start-up combustor **54**. More specifically, by operation of the air pump, the air is supplied to the oxygen-containing gas channel **124**. By adjusting the opening degree of the oxygen-containing gas regulator valve **126**, the air is supplied to the air supply pipe **57**.

In the meanwhile, in the raw fuel supply apparatus **14**, by operation of the fuel gas pump, for example, raw fuel such as the city gas (containing CH_4, C_2H_6, C_3H_8, C_4H_{10}) is supplied to the raw fuel channel **118**. By regulating the opening degree of the raw fuel regulator valve **120**, the raw fuel is supplied into the raw fuel supply pipe **58**. The raw fuel is mixed with the air, and supplied into the start-up combustor **54** (see FIGS. **3** and **4**).

Thus, the mixed gas of the raw fuel and the air is supplied into the start-up combustor **54**, and the mixed gas is ignited to start combustion. Therefore, the combustion gas produced in combustion flows from the first area R**1** to the second area R**2**. Further, the combustion gas is supplied to the third area R**3**, and then, the combustion gas is discharged to the outside of the fuel cell module **12** through the exhaust gas pipe **112**.

As shown in FIGS. **3** and **4**, the reformer **46** and the evaporator **48** are provided in the second area R**2**, and the heat exchanger **50** is provided in the third area R**3**. Thus, the combustion gas discharged from the first area R**1** first heats the reformer **46**, next heats the evaporator **48**, and then heats the heat exchanger **50**.

Then, after the temperature of the fuel cell module **12** is raised to a predetermined temperature, the air (oxygen-containing gas) is supplied to the heat exchanger **50**, and the mixed gas of the raw fuel and the water vapor is supplied to the reformer **46**.

More specifically, as shown in FIG. **1**, the opening degree of the oxygen-containing gas regulator valve **126** is adjusted such that the flow rate of the air supplied to the oxygen-containing gas supply pipe **110** is increased, and the opening degree of the raw fuel regulator valve **120** is adjusted such that the flow rate of the raw fuel supplied to the raw fuel supply channel **84** is increased. Further, by operation of the water supply apparatus **18**, the water is supplied to the water channel **88**. The air is supplied from the oxygen-containing gas supply pipe **110** to the heat recovery area **106** of the outer member **55**. Thus, the air flows through the holes **108** into the oxygen-containing gas supply chamber **102***a*.

Therefore, as shown in FIGS. **3** and **4**, the air flows into the heat exchanger **50**, and after the air is temporarily supplied to the oxygen-containing gas supply chamber **102***a*, while the air is moving inside the heat exchange pipes **96**, the air is heated by heat exchange with the combustion gas supplied into the third area R**3**. After the heated air is temporarily supplied to the oxygen-containing gas discharge chamber **102***b*, the air is supplied to the oxygen-containing gas supply passage **42***a* of the fuel cell stack **24** through the oxygen-containing gas pipes **114** (see FIG. **1**). In the fuel cell stack **24**, the heated air flows along the oxygen-containing gas flow field **38**, and the air is supplied to the cathode **28**.

After the air flows through the oxygen-containing gas flow field **38**, the air is discharged from the oxygen-containing gas discharge passage **42***b* into the oxygen-containing exhaust gas channel **63***a*. The oxygen-containing exhaust gas channel **63***a* is opened to the combustion cup **60** of the exhaust gas combustor **52**, and the oxygen-containing exhaust gas is supplied into the combustion cup **60**.

Further, as shown in FIG. **1**, the water from the water supply apparatus **18** is supplied to the evaporator **48**. After the raw fuel is desulfurized in the desulfurizer **122**, the raw fuel flows through the raw fuel supply channel **84**, and moves toward the reformer **46**.

In the evaporator **48**, after the water is temporarily supplied to the water supply chamber **82***a*, while water is moving inside the evaporation pipes **74**, the water is heated by the combustion gas flowing through the second area R**2**, and vaporized. After the water vapor flows into the water vapor discharge chamber **82***b*, the water vapor is supplied to the evaporation return pipe **90** connected to the water vapor discharge chamber **82***b*. Thus, the water vapor flows inside the evaporation return pipe **90**, and flows into the raw fuel supply channel **84**. Then, the water vapor is mixed with the raw fuel supplied by the raw fuel supply apparatus **14** to produce the mixed gas.

The mixed gas from the raw fuel supply channel **84** is temporarily supplied to the mixed gas supply chamber **78***a* of the reformer **46**. The mixed gas moves inside the reforming pipes **66**. In the meanwhile, the mixed gas is heated by the combustion gas flowing through the second area R**2**, and is then steam-reformed. After removal (reforming) of hydrocarbon of C_{2+}, a reformed gas chiefly containing methane is obtained.

After this reformed gas is heated, the reformed gas is temporarily supplied to the fuel gas discharge chamber **78***b* as the fuel gas. Thereafter, the fuel gas is supplied to the fuel gas supply passage **44***a* of the fuel cell stack **24** through the fuel gas channel **86** (see FIG. **1**). In the fuel cell stack **24**, the heated fuel gas flows along the fuel gas flow field **40**, and the fuel gas is supplied to the anode **30**. In the meanwhile, the air is supplied to the cathode **28**. Thus, electricity is generated in the electrolyte electrode assembly **32**.

After the fuel gas flows through the fuel gas flow field **40**, the fuel gas is discharged from the fuel gas discharge passage **44***b* to the fuel exhaust gas channel **63***b*. The fuel exhaust gas channel **63***b* is opened to the inside of the combustion cup **60** of the exhaust gas combustor **52**, and the fuel exhaust gas is supplied into the combustion cup **60**.

Under the heating operation by the start-up combustor **54**, when the temperature of the fuel gas in the exhaust gas combustor **52** exceeds the self-ignition temperature, combustion of the oxygen-containing exhaust gas and the fuel exhaust gas is started inside the combustion cup **60**. In the meanwhile, combustion operation by the start-up combustor **54** is stopped.

The combustion cup **60** has the holes **60***a*. Therefore, as shown in FIG. **3**, the combustion gas supplied into the combustion cup **60** flows through the holes **60***a* from the first area R**1** into the second area R**2**. Then, after the combustion gas is supplied to the third area R**3**, the combustion gas is discharged to the outside of the fuel cell module **12**.

In the first embodiment, the FC peripheral equipment **56** includes the first area R**1** where the exhaust gas combustor **52** and the start-up combustor **54** are provided, the annular second area R**2** around the first area R**1** and where the reformer **46** and the evaporator **48** are provided, and the annular third area R**3** around the second area R**2** and where the heat exchanger **50** is provided.

That is, the first area R**1** is provided at the center, the annular second area R**2** is provided around the first area R**1**, and the annular third area R**3** is provided around the second area R**2**. Heat waste and heat radiation can be suppressed suitably. Thus, improvement in the heat efficiency is achieved, thermally self-sustaining operation is facilitated, and the entire fuel cell module **12** can be made simple and compact. The thermally self-sustaining operation herein means operation where the operating temperature of the fuel cell **22** is maintained using only heat energy generated in the fuel cell **22** itself, without supplying additional heat from the outside.

The heat exchanger **50** includes the annular oxygen-containing gas supply chamber **102***a*, the annular oxygen-containing gas discharge chamber **102***b*, the heat exchange pipes **96**, and the third combustion gas channel **116***c*. The oxygen-containing gas is supplied to the oxygen-containing gas supply chamber **102***a*, and the heated oxygen-containing gas is discharged into the oxygen-containing gas discharge chamber **102***b*. Each of the heat exchange pipes **96** has one end connected to the oxygen-containing gas supply chamber **102***a*, and the other end connected to the oxygen-containing gas discharge chamber **102***b*. The third combustion gas channel **116***c* supplies the combustion gas to the space between the heat exchange pipes **96**.

Thus, simple structure is achieved easily. Accordingly, the production cost is reduced effectively. Further, by changing the volumes of the oxygen-containing gas supply chamber **102***a* and the oxygen-containing gas discharge chamber **102***b*, the length, the diameter, and the number of the pipes, a desired operation can be achieved depending on various operating conditions, and a wider variety of designs become available.

Further, in the first embodiment, the circumscribed non-uniform flow suppression plate **115** is provided along the minimum circumscribed circle which is tangent to the outer surfaces of the plurality of heat exchange pipes **96**. In the structure, as shown in FIG. **3**, the combustion gas which flows from the second area R**2** to the third area R**3** through the openings **72** is blown onto the circumscribed non-uniform flow suppression plate **115** facing the openings **72**.

Thus, the combustion gas moves along the circumscribed non-uniform flow suppression plate **115** in the direction indicated by the arrow Ld, and the combustion gas is also blown onto each of the heat exchange pipes **96** which are tangent to the circumscribed non-uniform flow suppression plate **115** and each of the heat exchange pipes **96** which are arranged inside the circumscribed non-uniform flow suppression plate **115**. After the combustion gas moves downward along one surface (inner surface) of the circumscribed non-uniform flow suppression plate **115** in the direction indicated by the arrow Ld, the combustion gas flows through the space formed at the lower end of the circumscribed non-uniform flow suppression plate **115**, and turns up. Thereafter, the combustion gas flows along the other surface (outer surface) of the circumscribed non-uniform flow suppression plate **115** in the direction indicated by the arrow Lu.

In the structure, after the combustion gas flows into the third area R**3**, by the guidance of the circumscribed non-uniform flow suppression plate **115**, the combustion gas flows along the outer surfaces of the heat exchange pipes **96** in the axial direction suitably. Thus, non-uniform flow and blow-through of the combustion gas are suppressed suitably, and the channel of the combustion gas can be sufficiently long. Accordingly, the quantity of the heat passed from the combustion gas to the oxygen-containing gas is increased, and improvement in the heat exchange efficiency is achieved suitably.

Further, as shown in FIG. **3**, the reformer **46** includes the annular mixed gas supply chamber **78***a*, the annular fuel gas discharge chamber **78***b*, the reforming pipes **66**, and the second combustion gas channel **116***b*. The mixed gas is supplied to the mixed gas supply chamber **78***a*, and the produced fuel gas is discharged into the fuel gas discharge chamber **78***b*. Each of the reforming pipes **66** has one end connected to the mixed gas supply chamber **78***a*, and the other end connected to the fuel gas discharge chamber **78***b*. The second combustion gas channel **116***b* supplies the combustion gas to the space between the reforming pipes **66**.

Thus, the structure is simplified easily, and the production cost is reduced effectively. Further, by changing the volumes of the mixed gas supply chamber **78***a* and the fuel gas discharge chamber **78***b*, the length, the diameter, and the number of the pipes, a desired operation can be achieved depending on various operating conditions, and a wider variety of designs become available.

The evaporator **48** includes the annular water supply chamber **82***a*, the annular water vapor discharge chamber **82***b*, the evaporation pipes **74**, and the second combustion gas channel **116***b*. The water is supplied to the water supply chamber **82***a*, and the water vapor is discharged into the water vapor discharge chamber **82***b*. Each of the evaporation pipes **74** has one end connected to the water supply chamber **82***a*, and the other end connected to the water vapor discharge chamber **82***b*. The second combustion gas channel **116***b* supplies the combustion gas to the space between the evaporation pipes **74**.

Thus, the structure is simplified easily, and the production cost is reduced effectively. Further, by changing the volumes of the water supply chamber **82***a* and the water vapor discharge chamber **82***b*, the length, the diameter, and the number of the pipes, a desired operation can be achieved depending on various operating conditions, and a wider variety of designs become available.

Further, the fuel cell module **12** is a solid oxide fuel cell module. Therefore, the fuel cell module **12** is suitable for, in particular, high temperature type fuel cells such as SOFC.

As shown in FIGS. **8**, **9**, and **10**, a fuel cell module **130** according to a second embodiment of the present invention includes a first circumscribed non-uniform flow suppression plate **132** and a second circumscribed non-uniform flow suppression plate **134** provided in the third area R**3** where the heat exchanger **50** is provided. The constituent elements of the fuel cell module **130** according to the second embodiment of the present invention that are identical to those of the fuel cell module **12** according to the first embodiment are labeled with the same reference numerals, and description thereof will be omitted. Further, also in third and other embodiments described later, the constituent elements that are identical to those of the fuel cell module **12** according to the first embodiment are labeled with the same reference numerals, and description thereof will be omitted.

As shown in FIG. **10**, the first circumscribed non-uniform flow suppression plate **132** has a cylindrical shape provided along the minimum circumscribed circle which is tangent to the outer surfaces of the plurality of heat exchange pipes **96** on an inner virtual circle. The second circumscribed non-uniform flow suppression plate **134** has a cylindrical shape provided along the minimum circumscribed circle which is tangent to the outer surfaces of the plurality of heat exchange pipe **96** on an outer virtual circle. For example, the first circumscribed non-uniform flow suppression plate **132** and the second circumscribed non-uniform flow suppression plate **134** are fixed to the heat exchange pipes **96** by welding or the like.

As shown in FIGS. **8** and **9**, for example, the first circumscribed non-uniform flow suppression plate **132** is made of a thin metal plate, and provided on a side closer to the exhaust gas combustor **52** in the pipe length direction of the heat exchange pipes **96** indicated by an arrow L. Specifically, the upper end of the first circumscribed non-uniform flow suppression plate **132** is fixed to the upper ring member **98***b*, and the lower end of the first circumscribed non-uniform flow suppression plate **132** is spaced upward from the lower ring member **98***a* by a predetermined distance h**1** (see FIG. **9**).

The second circumscribed non-uniform flow suppression plate **134** is made of a thin metal plate, and provided on a side away from the exhaust gas combustor **52** (i.e., a side closer to the start-up combustor **54**) in the pipe length direction of the heat exchange pipes **96** indicated by the arrow L. Specifically, the lower end of the second circumscribed non-uniform flow suppression plate **134** is fixed to the lower ring member **98***a*, and the upper end of the second circumscribed non-uniform flow suppression plate **134** is spaced downward from the upper ring member **98***b* by a predetermined distance h**2** (see FIG. **9**).

The third combustion gas channel **116***c* has a bent shape, in which gas is first directed to flow downward in a direction indicated by an arrow Ld by the first circumscribed non-uniform flow suppression plate **132**, and then directed to flow upward in a direction indicated by an arrow Lu by the second circumscribed non-uniform flow suppression plate **134**.

In the second embodiment, as shown in FIG. **9**, the combustion gas which flows from the second area R**2** to the third area R**3** through a plurality of openings **72** is blown onto the first circumscribed non-uniform flow suppression plate **132** facing the openings **72**.

Therefore, the combustion gas moves along the first circumscribed non-uniform flow suppression plate **132** in the direction indicated by the arrow Ld, and the combustion gas is blown onto each of the heat exchange pipes **96** (inner heat exchange pipes **96**) which are tangent to the first circumscribed non-uniform flow suppression plate **132**. After the combustion gas flows along the inner surface of the first circumscribed non-uniform flow suppression plate **132** in the direction indicated by the arrow Ld, the combustion gas flows through a space formed at the lower end of the first circumscribed non-uniform flow suppression plate **132**, and the combustion gas is blown onto the second circumscribed non-uniform flow suppression plate **134**.

In this manner, the combustion gas flows along the inner surface of the second circumscribed non-uniform flow suppression plate **134** in the direction indicated by Lu, and the combustion gas is blown onto each of the heat exchange pipes **96** (outer heat exchange pipes **96**) which are tangent to the second circumscribed non-uniform flow suppression plate **134**.

In the structure, after the combustion gas flows into the third area R**3**, by the guidance of the first circumscribed non-uniform flow suppression plate **132** and the second circumscribed non-uniform flow suppression plate **134**, the combustion gas flows along the outer surfaces of the heat exchange pipes **96** in the axial direction suitably. Thus, non-uniform flow and blow-through of the combustion gas are suppressed suitably, and the channel of the combustion gas can be sufficiently long. Accordingly, the same advantages as in the case of the first embodiment are obtained. For example, the quantity of the heat passed from the combustion gas to the oxygen-containing gas is increased, and improvement in the heat exchange efficiency is achieved suitably.

Further, among the first circumscribed non-uniform flow suppression plate **132** and the second circumscribed non-uniform flow suppression plate **134**, the first circumscribed non-uniform flow suppression plate **132** provided at a position closest to the center of the first area R**1** is positioned on a side closer to the exhaust gas combustor **52** in the pipe length direction. In the structure, the exhaust gas discharged from the exhaust gas combustor **52** can flow along the heat exchange pipes **96** still more smoothly and reliably by the guidance of the adjacent first circumscribed non-uniform flow suppression plate **132**. Accordingly, the quantity of the heat passed from the combustion gas to the oxygen-containing gas (air) is increased, and improvement in the heat exchange efficiency is achieved suitably.

As shown in FIGS. **11**, **12**, and **13**, a fuel cell module **140** according to a third embodiment of the present invention includes a circumscribed non-uniform flow suppression plate **142** provided in the second area R**2** where the reformer **46** and the evaporator **48** are provided. The circumscribed non-uniform flow suppression plate **142** has a cylindrical shape provided along the minimum circumscribed circle which is tangent to the outer surfaces of a plurality of reforming pipes **66** of the reformer **46**.

The upper end of the circumscribed non-uniform flow suppression plate **142** is fixed to the first upper ring member **68***b*, and the lower end of the circumscribed non-uniform flow suppression plate **142** is spaced upward from the first lower ring member **68***a* by a predetermined distance h**3** (see FIG. **11**). The circumscribed non-uniform flow suppression plate **142** may be provided along the minimum circumscribed circle which is tangent to the outer surfaces of the plurality of evaporation pipes **74** of the evaporator **48**.

In the third area R**3**, the circumscribed non-uniform flow suppression plate **115** is provided. However, this circumscribed non-uniform flow suppression plate **115** may be dispensed with as necessary. Alternatively, instead of the circumscribed non-uniform flow suppression plate **115**, the first circumscribed non-uniform flow suppression plate **132** and the second circumscribed non-uniform flow suppression plate **134** according to the second embodiment may be provided.

In the third embodiment, the combustion gas moves from the first area R**1** to the second area R**2** through a plurality of holes **60***a*. Then, the combustion gas is blown onto the circumscribed non-uniform flow suppression plate **142**. Therefore, the combustion gas moves along the circumscribed non-uniform flow suppression plate **142** in the direction indicated by the arrow Ld, and the combustion gas is blown onto each of the reforming pipes **66** which are tangent to the circumscribed non-uniform flow suppression plate **142**.

In the structure, after the combustion gas flows into the second area R**2**, by the guidance of the circumscribed non-uniform flow suppression plate **142**, the combustion gas flows along the outer surfaces of the reforming pipes **66** in the axial direction suitably. Thus, non-uniform flow and blow-through of the combustion gas are suppressed suitably, and the channel of the combustion gas can be sufficiently long. Accordingly, the same advantages as in the case of the first and second embodiments are obtained. For example, the quantity of the heat passed from the combustion gas to the reforming gas is increased, and improvement in the heat exchange efficiency is achieved suitably.

As shown in FIGS. **14** and **15**, a fuel cell module **150** according to a fourth embodiment of the present invention includes an inscribed non-uniform flow suppression plate **152** and a circumscribed non-uniform flow suppression plate **154** provided in the third area R**3** where the heat exchanger **50** is provided. One or two inscribed non-uniform flow suppression plates **152** are provided along the maximum inscribed circle(s) which is tangent to the outer surfaces of a plurality of outer (or inner or both of outer and inner) heat exchange pipes **96**. One or two circumscribed non-uniform flow suppression plates **154** are provided along the minimum circumscribed circle(s) which is tangent to the outer surfaces of the plurality of outer (or inner or both of outer and inner) heat exchange pipes **96**.

The inscribed non-uniform flow suppression plate **152** has a cylindrical shape. As shown in FIG. **14**, an upper end of the inscribed non-uniform flow suppression plate **152** is fixed to an upper ring member **98***b*, and a lower end of the inscribed non-uniform flow suppression plate **152** is spaced upward from a lower ring member **98***a*. A lower end of the circumscribed non-uniform flow suppression plate **154** is fixed to the lower ring member **98***a*, and an upper end of the circumscribed non-uniform flow suppression plate **154** is spaced downward from the upper ring member **98***b*.

In the fourth embodiment, in the third area R**3** where the heat exchanger **50** is provided, the circumscribed non-uniform flow suppression plate **154** is provided along the minimum circumscribed circle which is tangent to the outer surfaces of the plurality of heat exchange pipes **96**, and the inscribed non-uniform flow suppression plate **152** is provided along the maximum inscribed circle which is tangent to the outer surfaces of the heat exchange pipes **96**. The positions of the ends of the circumscribed non-uniform flow suppression plate **154** and the inscribed non-uniform flow suppression plate **152** are offset from each other (i.e., the ends are arranged in a staggered manner) in the pipe length direction.

In the structure, as shown in FIGS. **14** and **15**, the combustion gas flows into the third area R**3**, and flows downward along the inscribed non-uniform flow suppression plate **152**. Thereafter, the combustion gas flows below the inscribed non-uniform flow suppression plate **152**, and the combustion gas is blown onto the circumscribed non-uniform flow suppression plate **154**. Then, the combustion gas flows along a flow channel formed between the circumscribed non-uniform flow suppression plate **154** and the inscribed non-uniform flow suppression plate **152** in the direction indicated by the arrow Lu, and the combustion gas is blown onto the outer surfaces of the heat exchange pipes **96**.

Thus, non-uniform flow and blow-through of the combustion gas supplied to the heat exchanger **50** are suppressed suitably, and the combustion gas flows along the heat exchange pipes **96** still more smoothly and reliably. Accordingly, the same advantages as in the cases of the first to third embodiments are obtained. For example, the quantity of the heat passed from the combustion gas to the oxygen-containing gas is increased, and improvement in the heat exchange efficiency is achieved suitably.

As shown in FIG. **16**, a fuel cell module **160** according to a fifth embodiment of the present invention includes an inscribed non-uniform flow suppression plate **152** and a circumscribed non-uniform flow suppression plate **162** provided in the third area R**3** where the heat exchanger **50** is provided.

As shown in FIGS. **16** and **17**, the circumscribed non-uniform flow suppression plate **162** is provided along the minimum circumscribed circle which is tangent to the outer surfaces of a plurality of heat exchange pipes **96**, and includes inner protrusions **164** protruding between the heat exchange pipes **96**. The inner protrusions **164** protrude to the circumference of a virtual circle connecting the centers of the heat exchange pipes **96**, or to near the circumference, so that the circumscribed non-uniform flow suppression plate **162** contacts the outer surfaces of the heat exchange pipes **96** over the range of about 180°.

The cross sectional area of a combustion gas flow opening formed by the circumscribed non-uniform flow suppression plate **162**, the inscribed non-uniform flow suppression plate **152**, and the outer surfaces of the heat exchange pipes **96**, and the total sectional area of the heat exchange pipes **96** are set to be the same.

In the fifth embodiment, the circumscribed non-uniform flow suppression plate **162** has a substantially wavy shape, and contacts the outer surfaces of the heat exchange pipes **96**. Therefore, further improvement in the efficiency of heat exchange between the combustion gas and the oxygen-containing gas is achieved suitably. Further, since the cross sectional area of the combustion gas flow opening and the total cross sectional area of the heat exchange pipes **96** are set to be the same, improvement in the heat exchange efficiency is achieved, and thermally self-sustaining operation is facilitated.

Though the fifth embodiment is applied to the outer heat exchange pipes **96** of the heat exchanger **50**, the present invention is not limited in this respect. The fifth embodiment may be applied to the inner heat exchange pipes **96**. Further, the above structure may be applicable to the reformer **46** and the evaporator **48**.

While the invention has been particularly shown and described with reference to preferred embodiments, it will be understood that variations and modifications can be effected thereto by those skilled in the art without departing from the scope of the invention as defined by the appended claims.

The invention claimed is:

1. A fuel cell module comprising:

a fuel cell stack formed by stacking a plurality of fuel cells for generating electricity by electrochemical reactions of a fuel gas and an oxygen-containing gas;

a reformer for reforming a mixed gas of water vapor and a raw fuel chiefly containing hydrocarbon to produce the fuel gas supplied to the fuel cell stack;

an evaporator for evaporating water and supplying the water vapor to the reformer;

a heat exchanger for raising a temperature of the oxygen-containing gas by heat exchange with a combustion gas, and supplying the oxygen-containing gas to the fuel cell stack;

an exhaust gas combustor for combusting the fuel gas discharged from the fuel cell stack as a fuel exhaust gas and the oxygen-containing gas discharged from the fuel cell stack as an oxygen-containing exhaust gas to produce the combustion gas; and

a start-up combustor for combusting the raw fuel and the oxygen-containing gas to produce the combustion gas,

wherein the fuel cell module includes:

a first area where the exhaust gas combustor and the start-up combustor are provided;

an annular second area around the first area and where the reformer and the evaporator are provided; and

an annular third area around the second area and where the heat exchanger is provided,

wherein the heat exchanger includes an annular oxygen-containing gas supply chamber to which the oxygen-containing gas is supplied, an annular oxygen-containing gas discharge chamber to which the heated oxygen-containing gas is discharged, a plurality of heat exchange pipes each having one end connected to the oxygen-containing gas supply chamber and another end connected to the oxygen-containing gas discharge chamber, and a combustion gas channel for supplying the combustion gas to spaces between the heat exchange pipes; and

a circumscribed non-uniform flow suppression plate is provided along a minimum circumscribed circle which is tangent to outer surfaces of the plurality of heat exchange pipes.

2. The fuel cell module according to claim **1**, wherein the reformer includes an annular mixed gas supply chamber to which the mixed gas is supplied, an annular fuel gas discharge chamber to which the produced fuel gas is discharged, a plurality of reforming pipes each having one end connected to the mixed gas supply chamber and another end connected to the fuel gas discharge chamber, and a combustion gas channel for supplying the combustion gas to spaces between the reforming pipes; and

a circumscribed non-uniform flow suppression plate is provided along a minimum circumscribed circle which is tangent to outer surfaces of the plurality of reforming pipes.

3. The fuel cell module according to claim **1**, wherein the evaporator includes an annular water supply chamber to which the water is supplied, an annular water vapor discharge chamber to which the water vapor is discharged, a plurality of evaporation pipes each having one end connected to the water supply chamber and another end connected to the water vapor discharge chamber, and a combustion gas channel for supplying the combustion gas to spaces between the evaporation pipes; and

a circumscribed non-uniform flow suppression plate is provided along a minimum circumscribed circle which is tangent to outer surfaces of the plurality of evaporation pipes.

4. The fuel cell module according to claim **1**, wherein an inscribed non-uniform flow suppression plate is provided along a maximum inscribed circle which is tangent to the outer surfaces.

5. The fuel cell module according to claim **4**, wherein positions of ends of the circumscribed non-uniform flow suppression plate and the inscribed non-uniform flow suppression plate are offset from each other in a pipe length direction; and

the combustion gas flows between the circumscribed non-uniform flow suppression plate and the inscribed non-uniform flow suppression plate in the pipe length direction.

6. The fuel cell module according to claim **5** wherein, of the inscribed non-uniform flow suppression plate and the circumscribed non-uniform flow suppression plate, one that is provided at a position closest to the center of the first area is positioned on a side closer to the exhaust gas combustor in the pipe length direction.

7. The fuel cell module according to claim **1**, wherein the fuel cell module is a solid oxide fuel cell module.

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